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Mars Solar Rover Feasibility Study

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INTRODUCTION

The missions currently planned to place a unmanned rover on the surface of Mars all use radioisotope thermoelectric generators (RTGs) for the source of electric power. The only other source of power on Mars suitable to long term missions is solar power. In the past, solar power was not considered a useful source due to the distance from Mars to the Sun, the dust in the Martian atmosphere, and the day/night cycle.

Recently, several problems have surfaced that make the future use of RTGs difficult. The plutonium used to fuel them is in short supply, and the reactors that make this fuel are not operating. Making these reactors operational will require a large amount on capital, more than NASA may be willing to spend.

There are also safety issues associated with the use of plutonium. Although it is not very radioactive, plutonium is one of the most poisonous substances known. Containment of the plutonium in the event of a launch accident is mandatory. The current containment methods are believed adequate even for the case of the worst possible accident, and in fact some RTGs have survived launch failures intact. Because of this, the safety issue may be more of a perceived problem than a real one. However, even perceived problems can slow or stop a space mission, so this issue must be addressed.

Energy sources other than solar and nuclear do not appear to be useful on Mars. Stored chemical energy could not supply sufficient energy for the duration anticipated for the Mars rover sample return (MRSR) mission. The needed energy must be collected from the environment. Possible sources include temperature differences, geothermal heat, wind, and solar energy. Temperature differences, whether between different times of day, or different positions (for example between the air and the ground) are hard to use because they require large heat exchangers and a heat engine. Geothermal energy cannot be used by a rover, although it could one day prove useful for large fixed installations. Wind energy is probably insufficient due to the low air density on Mars. In addition, wind energy tends to be highly variable in both time and position, making it a difficult resource for a rover to rely on. Thus, direct solar power appears to be the only viable alternative to RTGs for a Mars rover. This report gives the results of an initial investigation into the feasibility of a Mars solar rover.

The first subject that must be addressed is the availability of solar energy on Mars. Factors that affect the amount of solar radiation received on a collector on the surface of Mars are the eccentricity of Mars' orbit, the Martian seasons, the time of day, the panel orientation, and the amount of dust in the atmosphere. Of these, the effects of the orbit, season, time, and panel orientation can be calculated. The effects of dust can be based on Viking lander data and theoretical models.

Once the resource has been quantified, the amount of energy that can be converted to a useful form can be determined. Two methods of conversion are investigated: photovoltaic conversion for electrical energy production, and thermal collectors to gather heat for the thermal control system. For the photovoltaics, both silicon and aluminum-gallium-arsenide gallium-arsenide heterojunction (abbreviated GaAs) types of cells are considered, along with two collector orientations, horizontal and tracking. For the thermal collectors, only simple flat-plate collectors are considered.

Sizing the solar panel requires quantification of the power needs of the rover. Power is needed for mobility, computation, data storage, science, communications, vehicle control, and thermal control. Each of these systems requires a varying amount of power depending on the operational mode of the rover. An average power requirement can be found by examining a possible operating scenario that defines the baseline case. When this is done, the average power use is found to be only about 10 percent more than the power used by the rover when it is in idle mode. The rover spends 72 percent of the time in idle mode. Because of this, the possibility of a rover with reduced energy needs is examined, where the reduction is to be achieved by reducing the power needs of the idle mode.

Use of solar power requires energy storage. For the electrical energy, batteries are used. The driver for the battery store size is the need to survive the night. The batteries also influence the size of the solar panel, as a portion of the energy stored and later retrieved from them is lost. For the thermal energy store, a phase-change material is assumed. Due to the temperatures involved, water is an acceptable material.

With the output of the various types of collectors determined, and the energy needs of the rover specified, the size of the required collector can be found. This is done for three cases: a panel that can provide an average of 500 watts, the same power as the RTG of the current MRSR rover; a combined electric and thermal collection panel to handle the baseline case; and a combined panel to handle the case with the reduced power idle mode.

The conclusions of this program are as follows:

- The available solar power on a horizontal panel averages over 100 watts per square meter for most of Mars for most of the year.

- The amount of power that can be collected averages 17 to 20 watts per square meter for photovoltaics, and 60 watts per square meter for thermal collectors, for areas of Mars with a 100 watt per square meter resource.

- The power needs of the baseline rover average 256 watts electrical and 50 watts thermal, including the storage losses. If the idle mode, which currently consumes 240 watts, is replaced by a sleep mode, which consumes 80 watts (and in both cases 50 of those watts are thermal), then the average power requirements drop to 116 watts electrical and 50 watts thermal.

- The required panel size is 25 square meters, if an average power output of 500 watts is required, corresponding to the current design using an RTG. For the baseline rover using combined electric and thermal collection, the panel size is 13.63 square meters. For the case with the sleep mode, the panel size is 6.63 square meters.

The recommendations from this study are the following:

- Improved models for the solar resource on Mars, as well as the amount of the resource that can be converted to useful forms of energy, should be developed.

- Methods for reducing the power needs of the rover should be investigated. These should include both component efficiency improvements and energy management improvements, such as introduction of a sleep mode.

- Rover configurations more conducive to solar power should be developed. Such configurations would have large areas suitable for mounting solar collectors with little or no need for deployable structures and would make allowances for camera and antenna placement so that the solar collectors would be shadowed as little as possible.

- Experimental data are needed on the long term effects of the Martian environment on the efficiency of solar collectors on Mars. This may require that a small, simple probe be sent to Mars for this purpose. A somewhat more complex probe could also be sent, for example a small rover. Such a rover could be used to test the Martian surface in order to determine whether there are any problems with mobility, before a larger, more expensive rover is sent.

Section 2
SOLAR POWER PRODUCTION

2.1 Solar Availability

To examine the feasibility of a photovoltaic power system for an unmanned Mars rover, the solar radiation levels on the Mars surface must first be determined. The total radiation reaching a Martian surface is the sum of the direct solar radiation and a diffuse component resulting from scattering in the atmosphere and reflection from surrounding surfaces. Estimates for these quantities are based on information provided by Appelbaum (1989).

2.2 Direct Solar Radiation

The following equations are used to estimate the direct solar radiation on a horizontal surface as a function of season, latitude, time of day and optical depth of the atmosphere. The direct radiation, I_b, is:

$$I_b = I_o \cos(\beta)\, e^{-(\tau/\cos(\beta))}$$

where the zenith angle β is given by:

$$\cos(\beta) = \sin(\phi)\sin(\delta) + \cos(\phi)\cos(\delta)\cos(h)$$

ϕ = latitude

δ = solar declination.

L_s is the Areocentric longitude defined as the position of Mars in its orbit measured from the Martian vernal equinox. Thus:

At $L_s = 270°$ (N. Hemisphere winter), $\delta = -24.8°$

At $L_s = 90°$ (N. Hemisphere summer), $\delta = 24.8°$

h = hour angle (0 at zenith; + to the west).

I_o is the solar radiation on a surface normal to the sun's rays beyond the Martian atmosphere and is given by:

$$I_o = 590(1 + ecc(\cos(L_s - 245)))^2/(1 - ecc^2)^2 \quad (W/m^2)$$

where the eccentricity, ecc = 0.093377.

Here, τ is the optical depth, a dimensionless quantity which determines the reduction in the direct radiation due to scattering in the atmosphere. A value for τ of 0.5 has been assumed for clear sky conditions, and 2.0 for dust storm conditions. Higher values for τ occur, but they are rare and do not last long.

Because the Martian orbit is elliptical, I_o varies from a maximum of 718 W/m^2 to a minimum of 493 W/m^2. The variation in I_o is shown in Figure 2-1. Aphelion occurs at $L_s = 69°$ and perihelion at $L_s = 249°$.

To begin the examination of the insolation levels, the diurnal variation at the equator was estimated for $L_s = 90°$ (summer in north hemisphere) and $L_s = 270°$ (winter in northern hemisphere) for an assumed optical depth of zero. These estimates are shown in Figure 2–2. The average for the daylight portion of a sol (one Martian day) at $L_s = 90°$ is 321 W/m^2, and for $L_s = 270°$, the daily average is 451 W/m^2. An optical depth of zero is not realistic, so in Figure 2-3 the estimates of the direct insolation for an optical depth of 0.5 are summarized. With this value for the optical depth, the attenuation in the direct insolation reduces the daylight average values to 155 and 217 W/m^2 for $L_s = 90°$ and $L_s = 270°$, respectively. That is, the direct radiation is reduced by approximately half by scattering in the atmosphere (assuming an optical depth of 0.5). The total insolation will not, however, be reduced by this amount, because there will be an increase in the diffuse component.

Estimates of solar insolation have also been made for a location with a latitude of 45° N. These results are shown in Figure 2-4. During the summer, the average daylight insolation is 195 W/m^2, which is comparable to values at the equator. However, during the winter, the daylight average falls dramatically to only 20 W/m^2, making operation of a solar-powered vehicle this far north possible only during the summer.

The above estimates have been calculated assuming the solar array is a horizontal surface. If the array tracks the sun, so that its surface normal is parallel to the incident solar rays, the insolation value can be increased. Results for a tracking array are shown in Figure 2-5. By tracking, the average daylight insolation can be increased from 217 to 301 W/m^2 for $L_s = 270°$ and from 155 to 214 W/m^2 for $L_s = 90°$. There is a penalty for tracking in that power must be used to provide the sensing and tracking and additional mass is required for

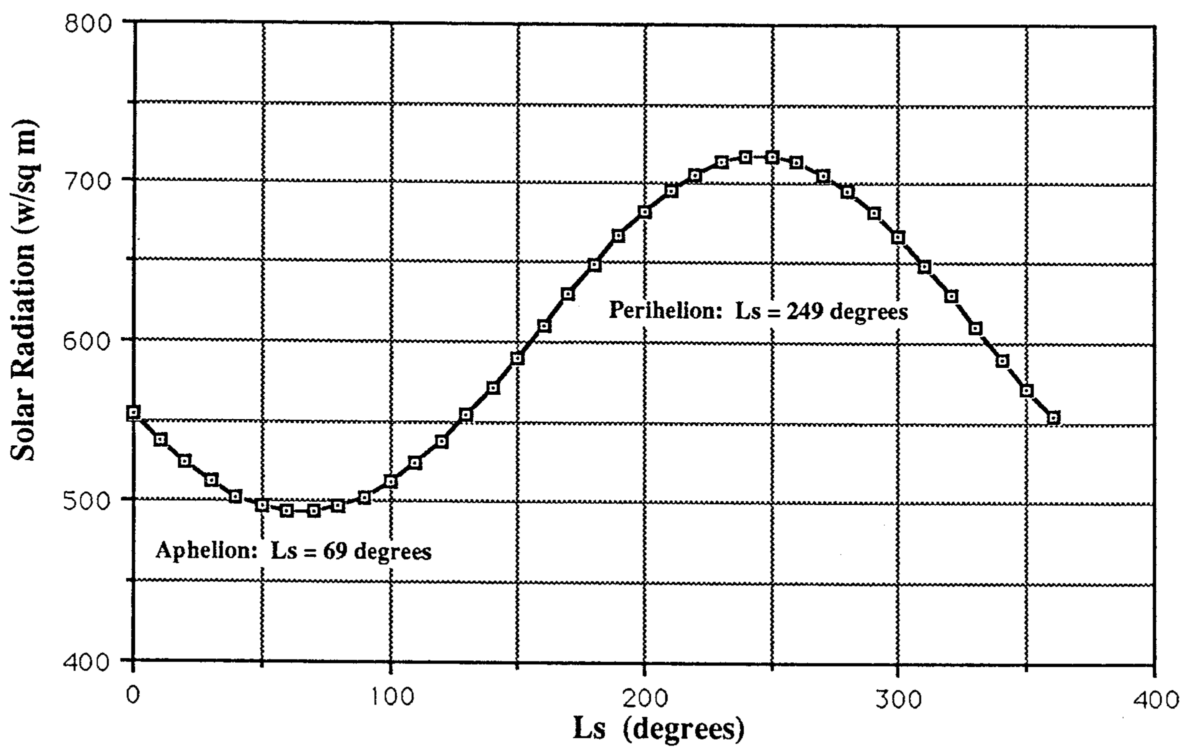

Figure 2-1. Solar radiation intensity at Mars, normal incidence, zero optical depth

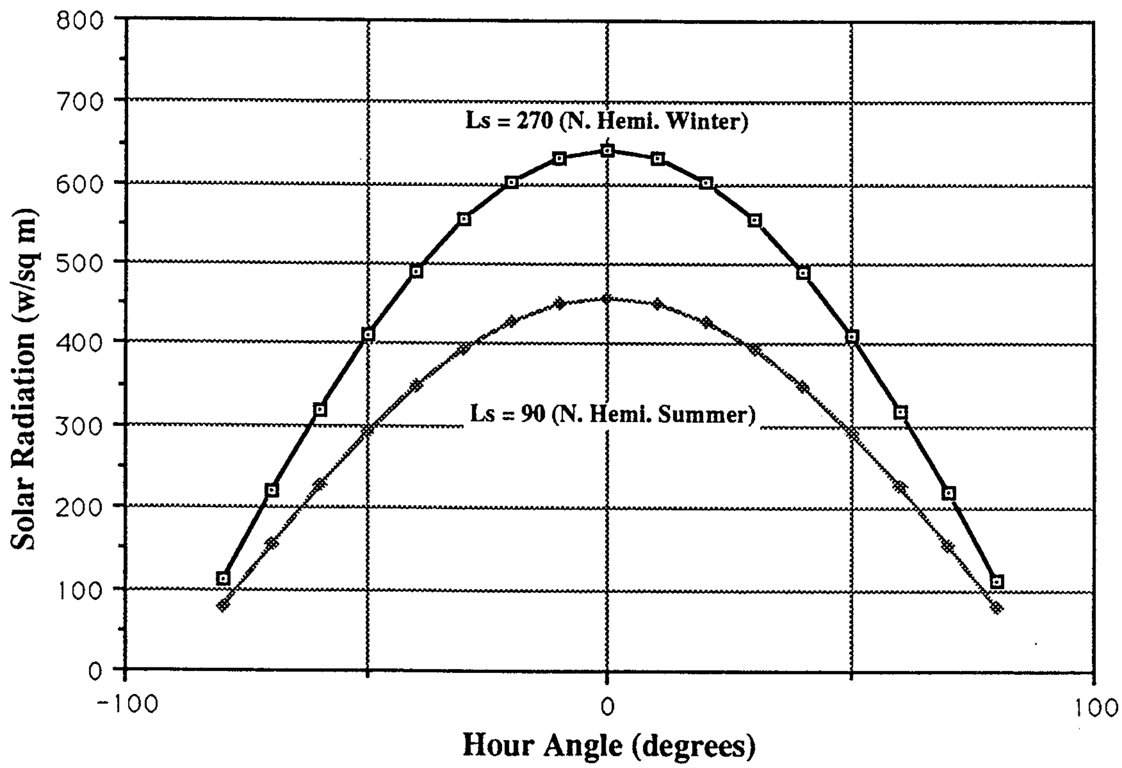

Figure 2-2. Diurnal variation of direct radiation at equator (horizontal surface), optical depth = 0.

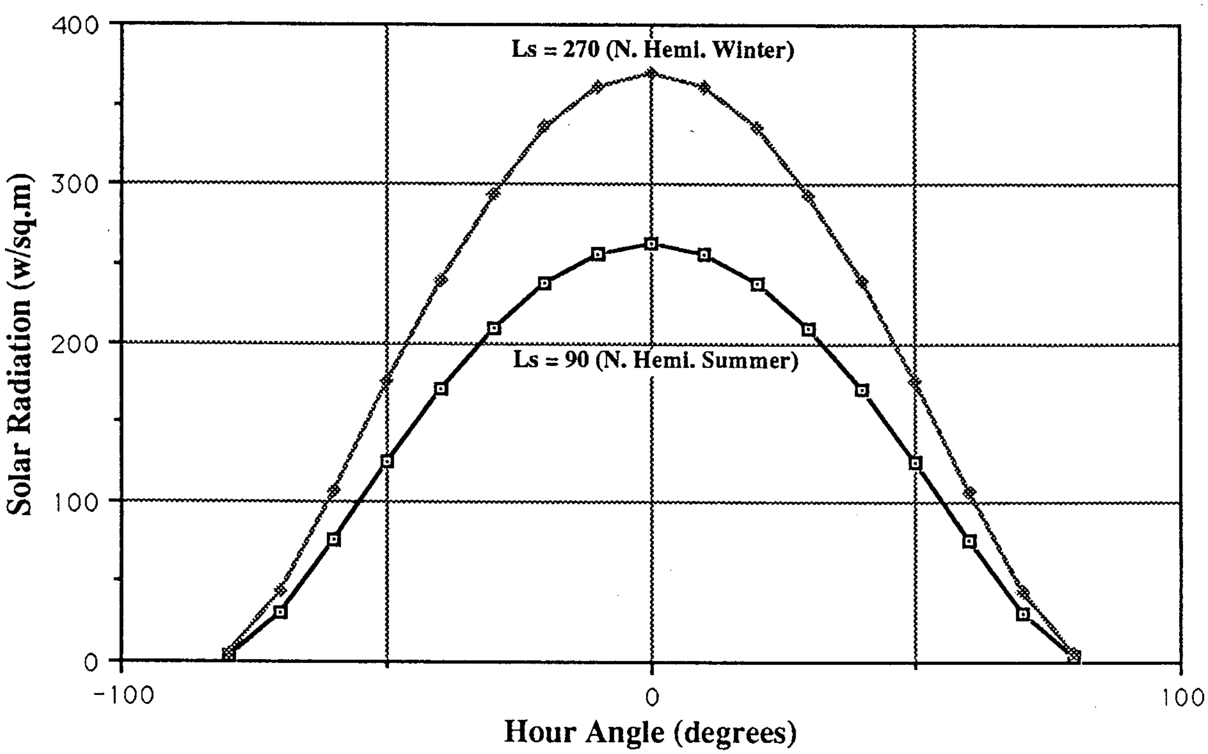

Figure 2-3. Diurnal variation of direct radiation at equator (horizontal surface), optical depth = 0.5.

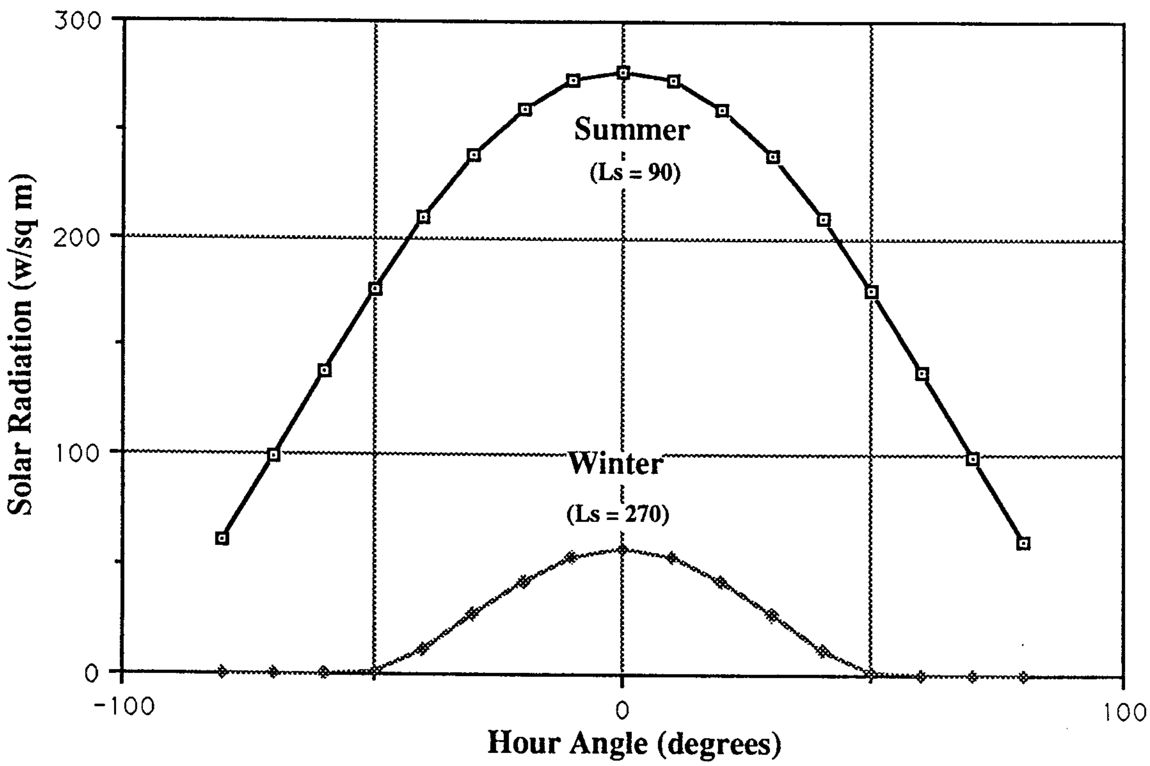

Figure 2-4. Diurnal variation of direct radiation at 45 degrees north (horizontal surface), optical depth = 0.5

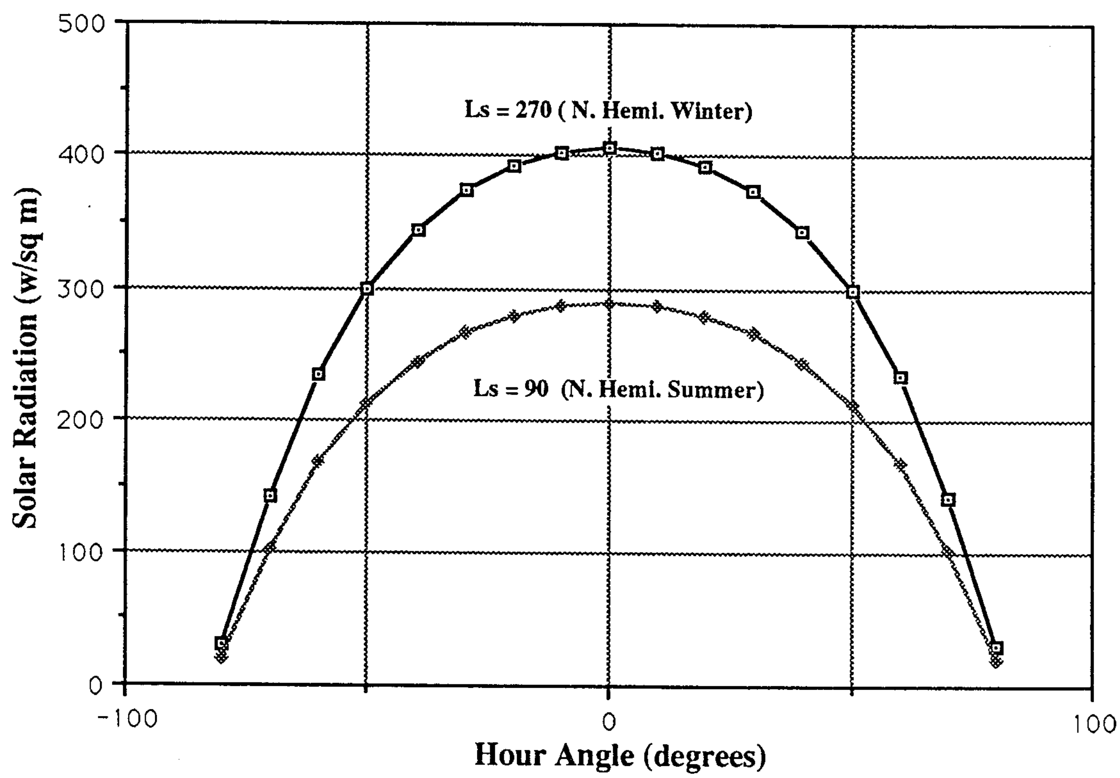

Figure 2-5. Diurnal variation of direct radiation at equator (tracking surface), optical depth=0.5.

motors, sensors and linkages. This additional power requirement can be estimated by referring to the power required to track and move the communications antenna, as shown in the Phase 1 design data book (Muirhead, 1988). To move a 1-kg antenna dish requires 15 watts. So if, for example, if a 10 m^2 panel at 2 kg/m^2 is required to provide the necessary power, then 300 watts is necessary for tracking. This is not, of course, a continuous requirement, but would made at discrete time intervals.

2.3 Diffuse Radiation

In the previous section, it was shown that the atmospheric dust reduces the direct radiation by 40 percent when the optical depth is 0.5, which is considered clear conditions. In dusty conditions when the optical depth is 2.0, the direct radiation can be reduced to 14 percent of the level in space. Fortunately for the use of solar power on Mars, much of the loss in direct radiation is still available as scattered radiation. Appelbaum gives predictions for the total radiation, the sum of the direct and scattered components, for a wide range of optical depths and solar elevation angles. Using these, the total available solar intensity on Mars can be found.

The optical depths that occur most of the time can be determined from the Viking lander data. A summary of this data is shown in Figure 2-6 for Lander number one and in Figure 2-7 for Lander number 2. For a large portion of the year the optical depth is about 0.5. In the later part of the year the global dust storms occur, raising the optical depth. For lander number one, the dust storm causes a peak optical depth of about three. For the other lander, the maximum is about two. For both landers, the optical depth is rarely greater than two. The higher optical depths tend to only occur when Mars is near perihelion, so the reduced insolation due to dust is compensated for by being closer to the sun. For design purposes, a optical depth range of 0.5 to 2.0 was selected as typical operating conditions. When higher optical depths occur, rover operations will have to be modified to accommodate the reduced power production.

Figure 2-8 shows G_h, the available solar power on a horizontal plate for several solar zenith angles as a function of atmospheric optical depth. The region of the plot that covers those optical depths that occur most of the time is $\tau = 0.5$ to 2.0. For this plot, the in-space intensity of the solar energy is 590 watts per square meter, the average value for Mars over the course of a orbit. As shown in the plot, the effect of dust on the total radiation level is not great, about 10 percent loss for a optical depth of 0.5, to 40 percent loss for an optical depth of 2.0.

Integration over one Martian day, a sol, gives the solar energy available. The results of this

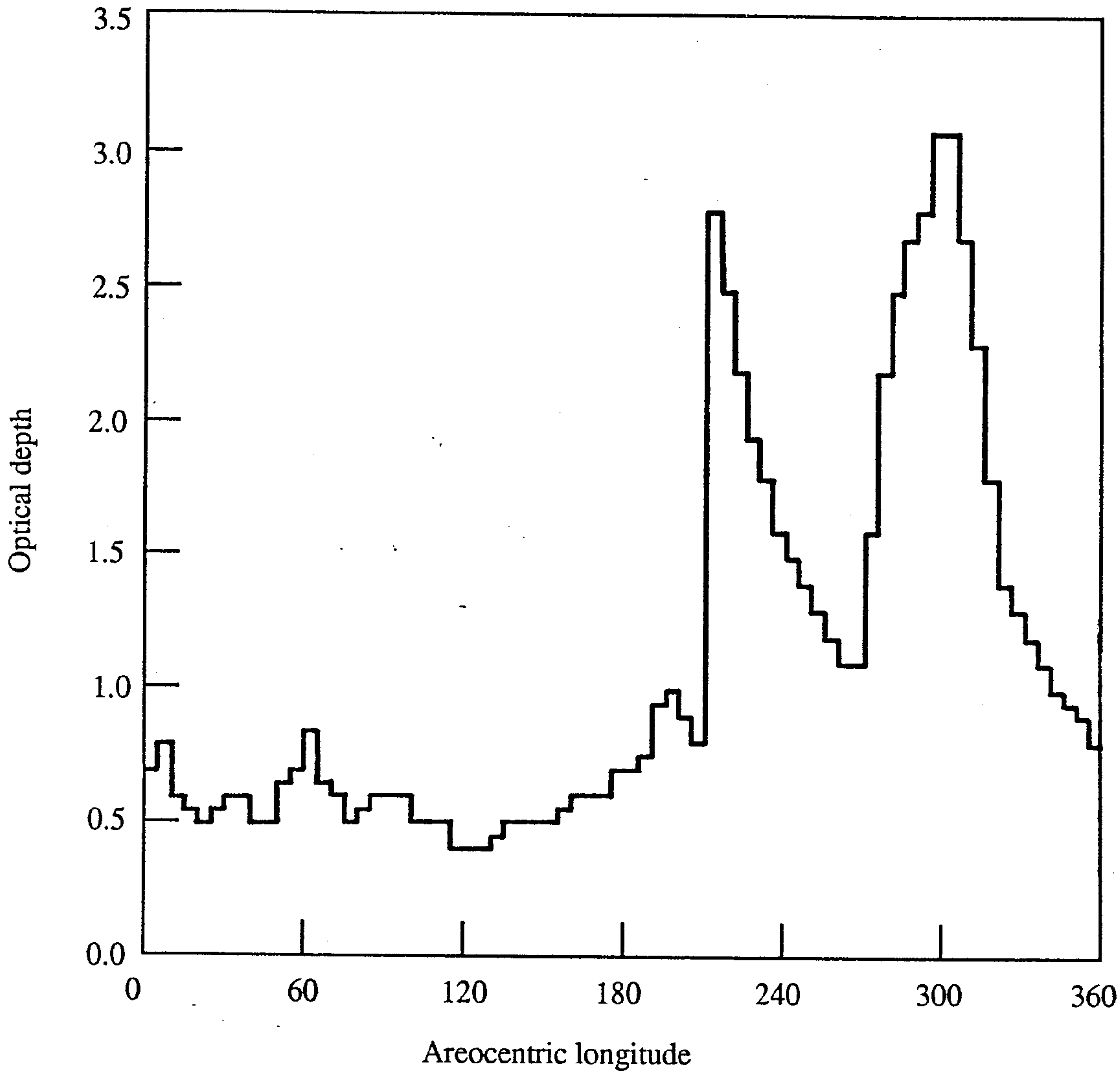

Figure 2-6. Optical depth history at Viking lander one.

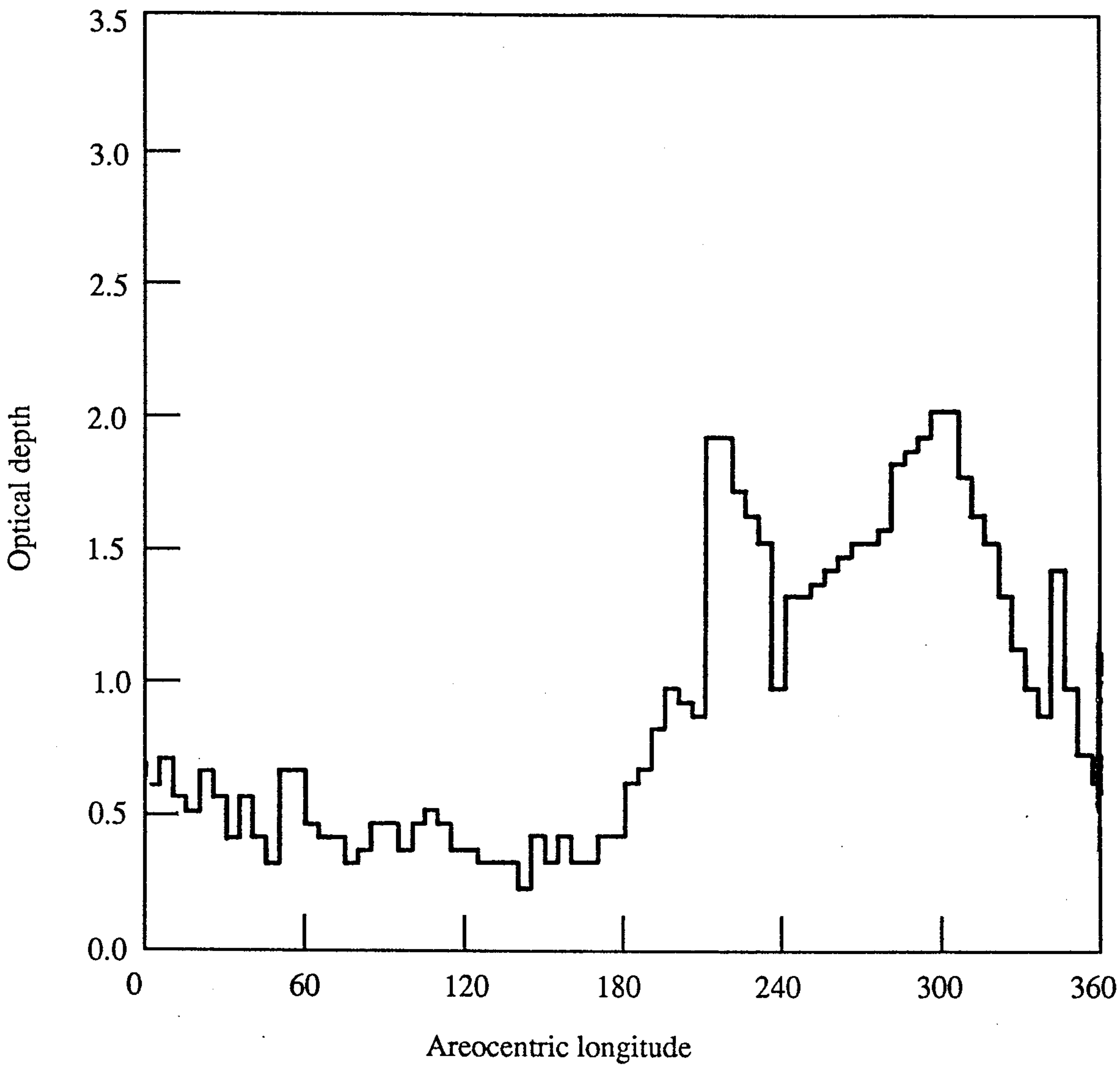

Figure 2-7. Optical depth history at Viking lander two.

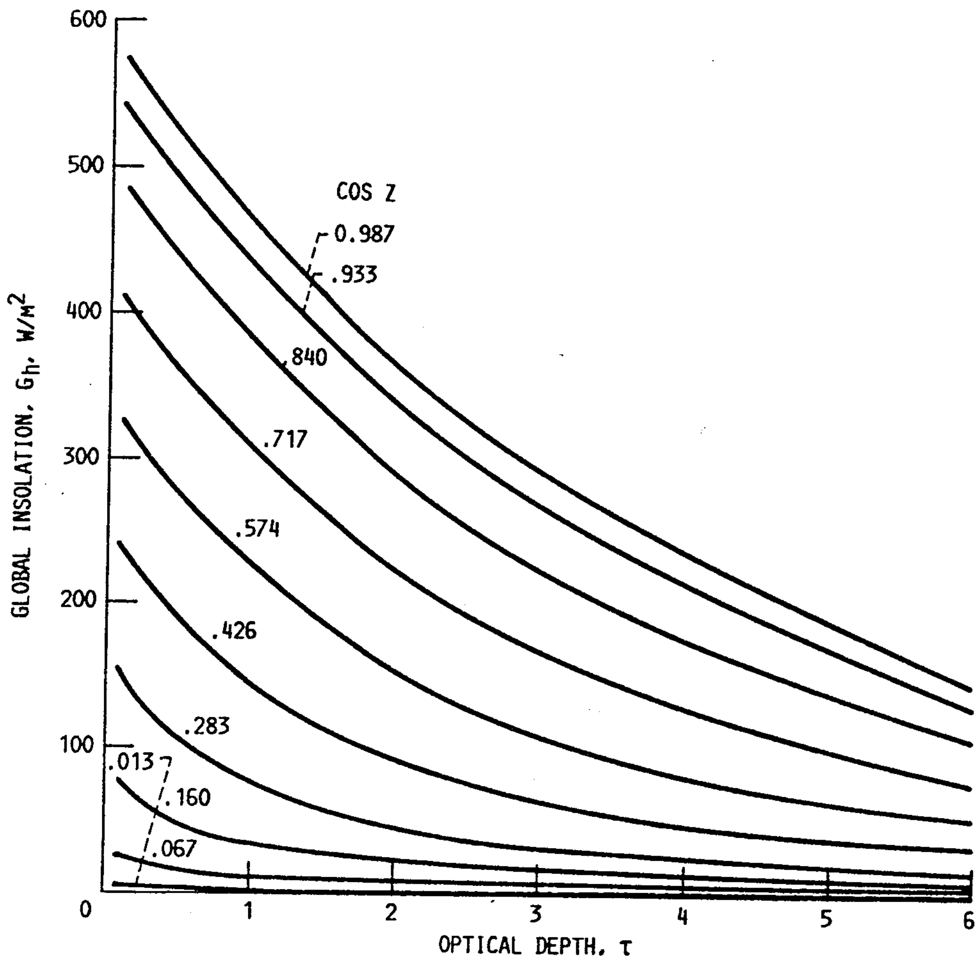

Figure 2-8. Variation of total insolation (direct plus scattered) on a horizontal surface with optical depth.

integration are shown in Figure 2-9 for the case of an optical depth of 0.5, and in Figure 2-10 for the case of an optical depth of 2.0. In both figures, the available energy averaged over a entire sol is shown for several latitudes and areocentric longitudes.

These figures indicate that 100 watts per square meter are available in most locations and in most seasons on Mars. The maximum availability occurs in the southern summer, at over 220 watts per square meter. At an optical depth of 2.0 due to a moderately severe dust storm, the availability is reduced to about 66 percent of the clear condition.

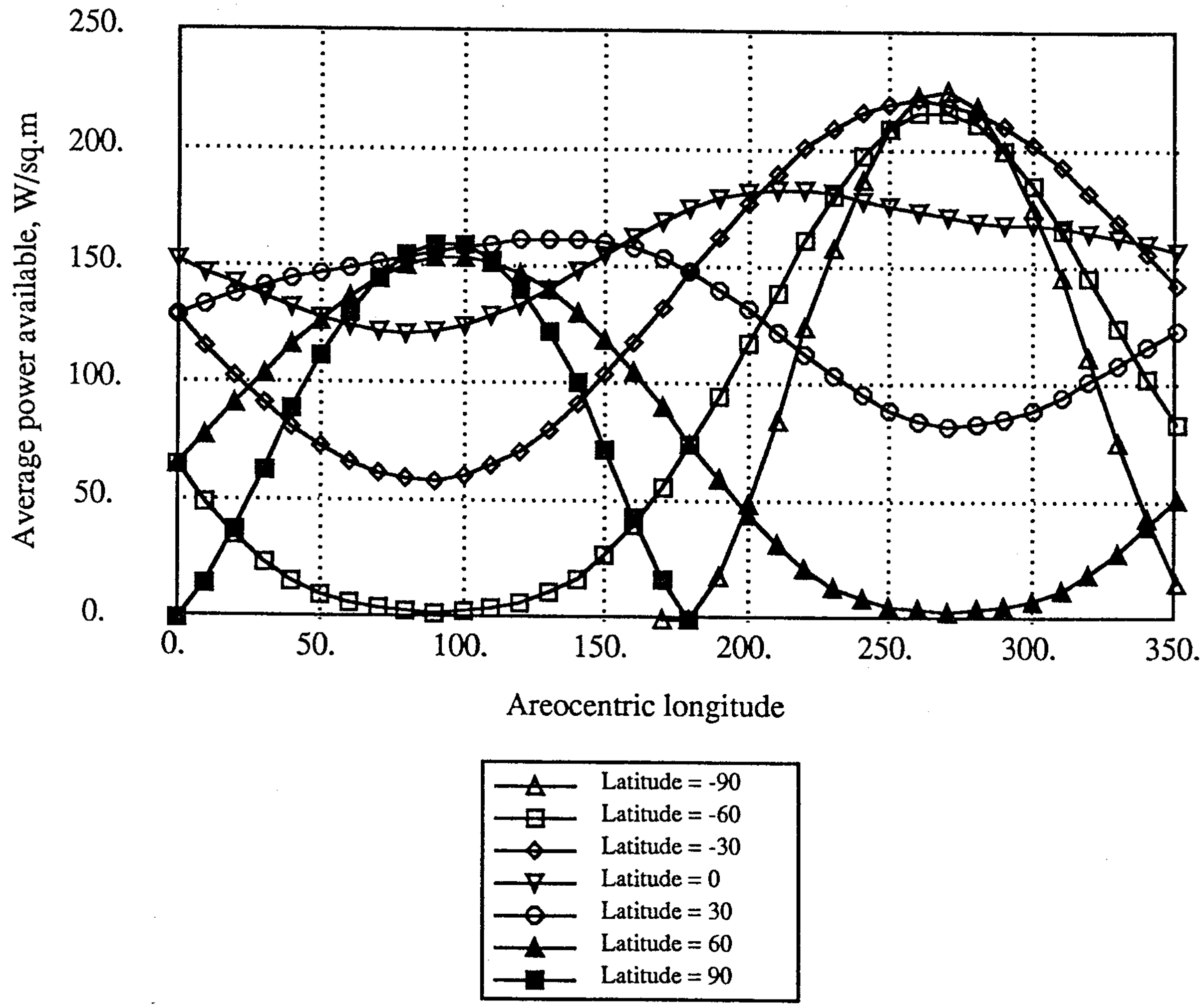

Figure 2-9. Solar energy available for a horizontal surface on Mars, optical depth = 0.5

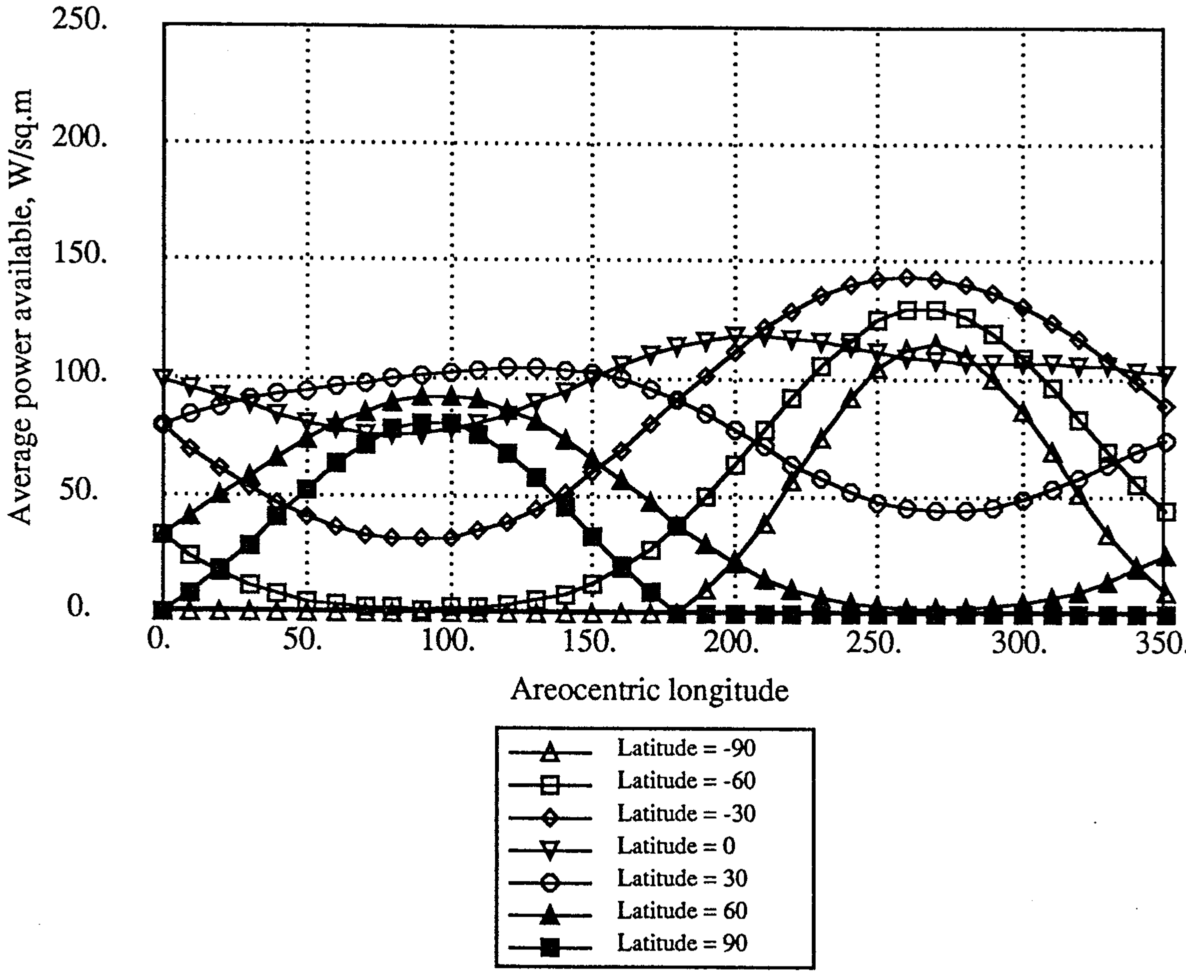

Figure 2-10. Solar energy available for a horizontal surface on Mars, optical depth = 2.0

Section 3
SOLAR ELECTRIC ENERGY PRODUCTION

3.1 Model Description

In this study, the level of analysis used for modeling the production of electrical power from solar cells is kept fairly simple. The effects taken into account are the solar intensity, both direct and scattered, the cell material, and the cell temperature. The effects not taken into account are the radiation scattered off the ground, the change in the panel's efficiency due to radiation level, except as it affects temperature, and the second order effects of heating and cooling on cell temperature. In determining the cell temperature, only the effects of the incoming solar radiation and black body radiation from the front of the panel are included. The effects of cooling from the Martian atmosphere, heating from scattered and emitted radiation of the ground, and infrared radiation emitted from atmospheric dust were ignored.

3.2 Cell Temperature and Efficiency

The solar panel has three main paths for gaining and losing energy: incoming solar radiation, electrical energy production, and black body radiation from its front surface. Other paths also exist. Thermal exchange with the ground is possible; however, the ground can be expected to have a temperature close to that of the panel, as both are exposed to the same sun, and the back of the cells is somewhat insulated by their supporting structure. Thus, the effects of the ground will be ignored. The Martian atmosphere can be expected to cool the panel to some extent. On Earth, a solar panel will lose about half its heat to the air by convective cooling, the rest by black body radiation. On Mars, with its lower atmospheric density, convective cooling can be expected to be a small effect, so it will be ignored here. Atmospheric dust will also radiate black body radiation to the cells. However, the dust is cold and fine, resulting in low levels of infrared radiation. With these simplifying assumptions, the only terms that remain are the solar input, electrical production, and the cell's black body radiation. The temperature of the cell can now be found.

The incoming energy to the cell that is not converted into electricity, and will be reradiated as black body radiation is

$$\text{energy input} = I\,(1 - \varepsilon)$$

where I is the incoming solar radiation and ε is the efficiency of the solar cells. The efficiency is modeled as a simple function of temperature:

$$\varepsilon = \varepsilon_o (1 - \alpha T)$$

where ε_o is the extrapolated efficiency of the cell at absolute zero, α is the reduction in cell output per degree, and T is the absolute temperature. The values used for the constants ε_o and α for typical GaAs (Flood, 1989) and silicon cells (Sturtevant, 1989) are given in Table 3-1.

Table 3-1

Cell type	Efficiency at 25 C	ε_o	α
GaAs	21.5%	0.3095	1.0243×10^{-3}
Silicon	15.0%	0.350	1.917×10^{-3}

The energy lost in the form of black body radiation is

$$\text{Energy lost} = 5.67 \times 10^{-8}\, T^4\ \text{W/m}^2.$$

The equations for energy input and energy lost can be equated and solved for temperature. This assumes that the solar cells are in a state of thermal equilibrium at all times, i.e., their thermal mass is low so there is no appreciable lag in temperature when they are warming up or cooling down. This procedure also assumes that the cell's absorptance and emittance are about equal to one.

The resulting equation is

$$I (1 - \varepsilon_o (1 - \alpha T)) = 5.67 \times 10^{-8}\, T^4$$

which can be solved for T. The temperature is then used to find the cell efficiency.

3.3 Solar Input

The solar input to the cells was calculated for two panel geometries: a horizontal panel and a tracking panel. In the case of the tracking panel, the added solar input due to scattered light from the ground was ignored. The effects of the eccentricity of the Martian orbit, the latitude of the panel, and the atmospheric dust were taken into account as described in Section 2. Calculations were carried out in Section 2 for optical depths of 0.5 (clear condition) and 2.0 (dusty conditions).

3.4 Energy Calculations

Given the above equations, the energy production of a solar panel can be found. For a particular season and time of day, the incoming solar energy can be found from the equations in Section 2.2. The effects of the atmospheric dust on the incoming radiation can be found from Figure 2-6. The equations in Section 3.2 can then be used to find the cell temperature, and hence the efficiency and power output.

The average energy production of a solar panel was found using the above method. The panel output was averaged over an entire Martian day, one sol. Calculations were carried out for seven latitudes on Mars (-90, -60, -30, 0, 30, 60, and 90 degrees), the complete range of areocentric longitudes, the two types of cells (GaAs and silicon), two optical depths (0.5 and 2.0), and two panel geometries (horizontal and tracking). The results are shown in Figures 3-1 to 3-8. If the average power for the daylight portion of the day is desired, then the Figure 3-1 to 3-8 results can be divided by the fraction of the sol that has daylight, given in Figure 3-9.

The effects of dust storms can be seen by comparing the results for the low and high optical depth cases. To a first approximation, the increased optical depth reduces the energy production by 30 to 40 percent. This reduction only applies for the latter half of the year, when Mars is near perihelion, and is compensated for by the distance reduction to the sun.

The results indicate that the advantage of the GaAs cells over the silicon cells is small, because the low temperatures at which the cells are operating is more advantageous to silicon than GaAs. An example time history of cell temperature is shown in Figure 3-10. Comparing this predicted temperature with measured air temperatures, it is found that the cell temperature is within 50 degrees of the air temperature.

The effect of using a tracking collector is to increase the energy production by about 50 percent over a non–tracking collector. This estimate is somewhat high, however. In making it, an assumption was made that all of the incoming light came from the direction of the sun. Due to the effects of the dust, this is not a correct assumption. If most of the scattering is forward scattering, then this assumption is close to correct, and if the scattering is more isotropic, then it is a poor one. Thus, these results for a tracking collector should be viewed as a upper limit. A further complication to this issue is that the both the scattering and the photovoltaic cell efficiency are

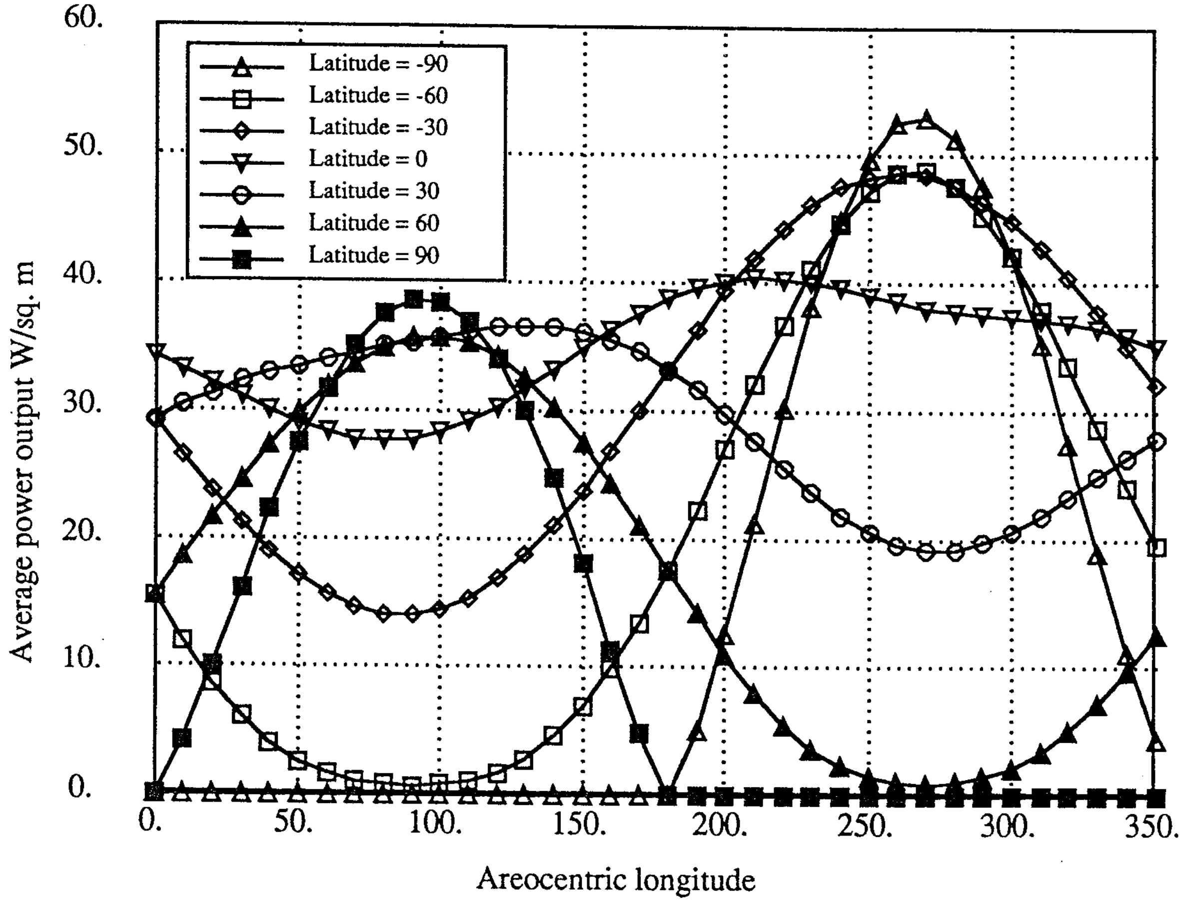

Figure 3-1. Solar panel average power output for a nontracking, horizontal Ga As panel with a optical depth of 0.5.

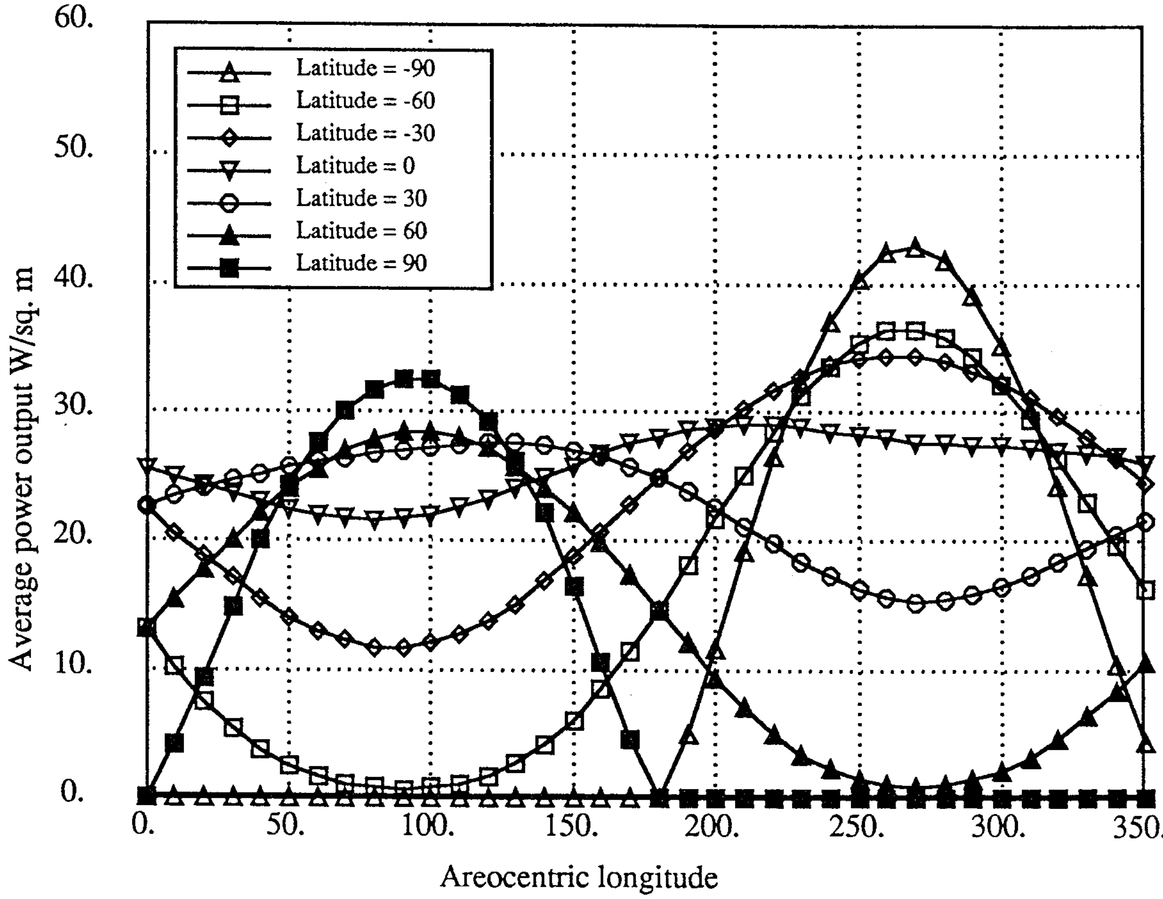

Figure 3-2. Solar panel average power output for a nontracking, horizontal Silicon panel with a optical depth of 0.5.

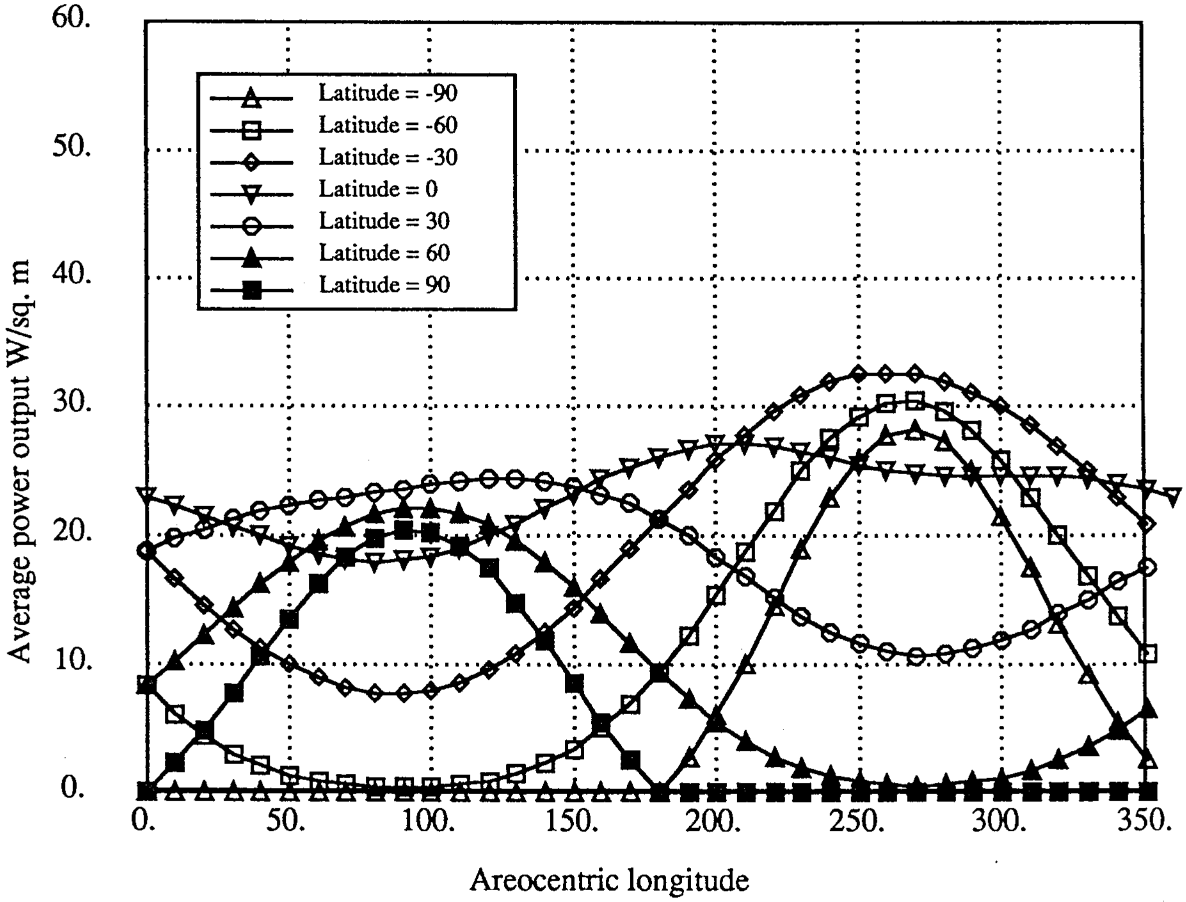

Figure 3-3. Solar panel average power output for a nontracking, horizontal Ga As panel with a optical depth of 2.0.

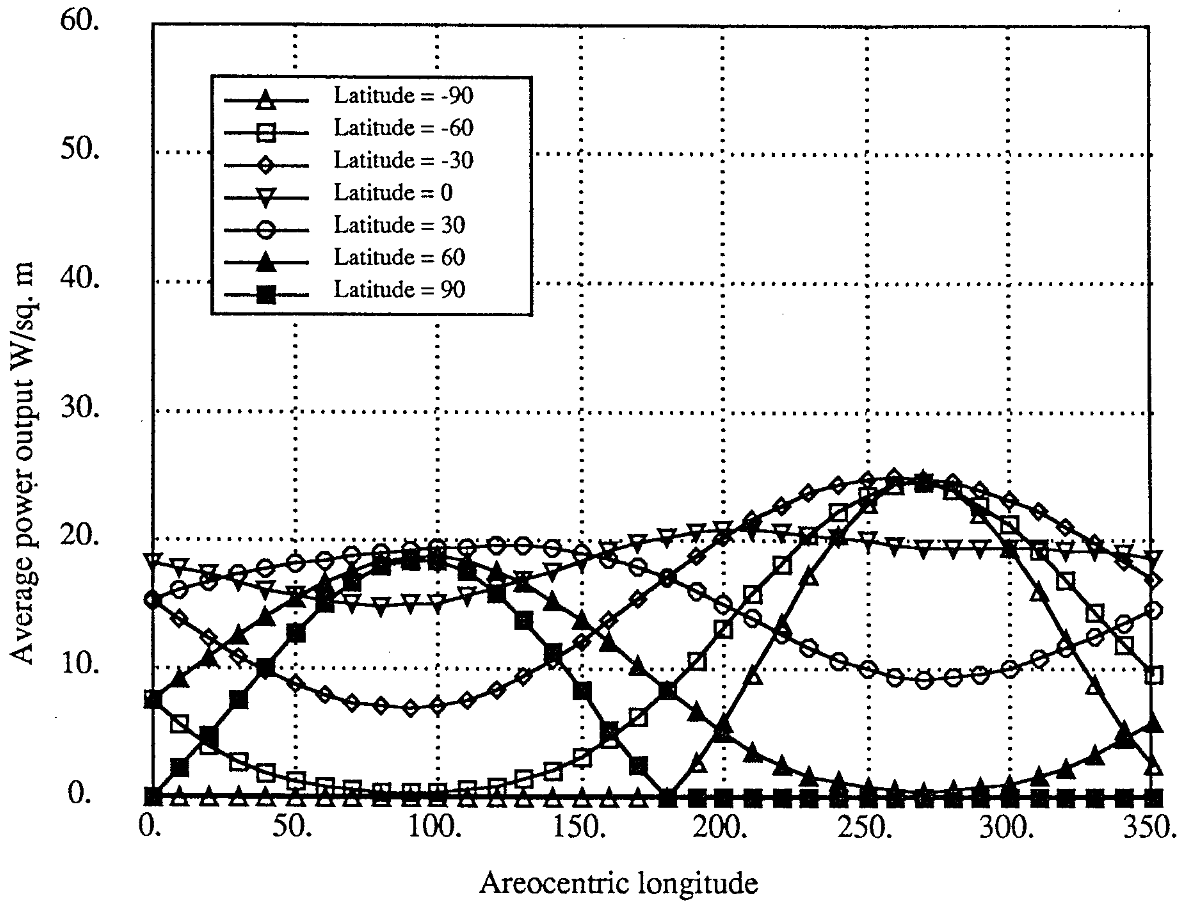

Figure 3-4. Solar panel average power output for a nontracking, horizontal Silicon panel with a optical depth of 2.0.

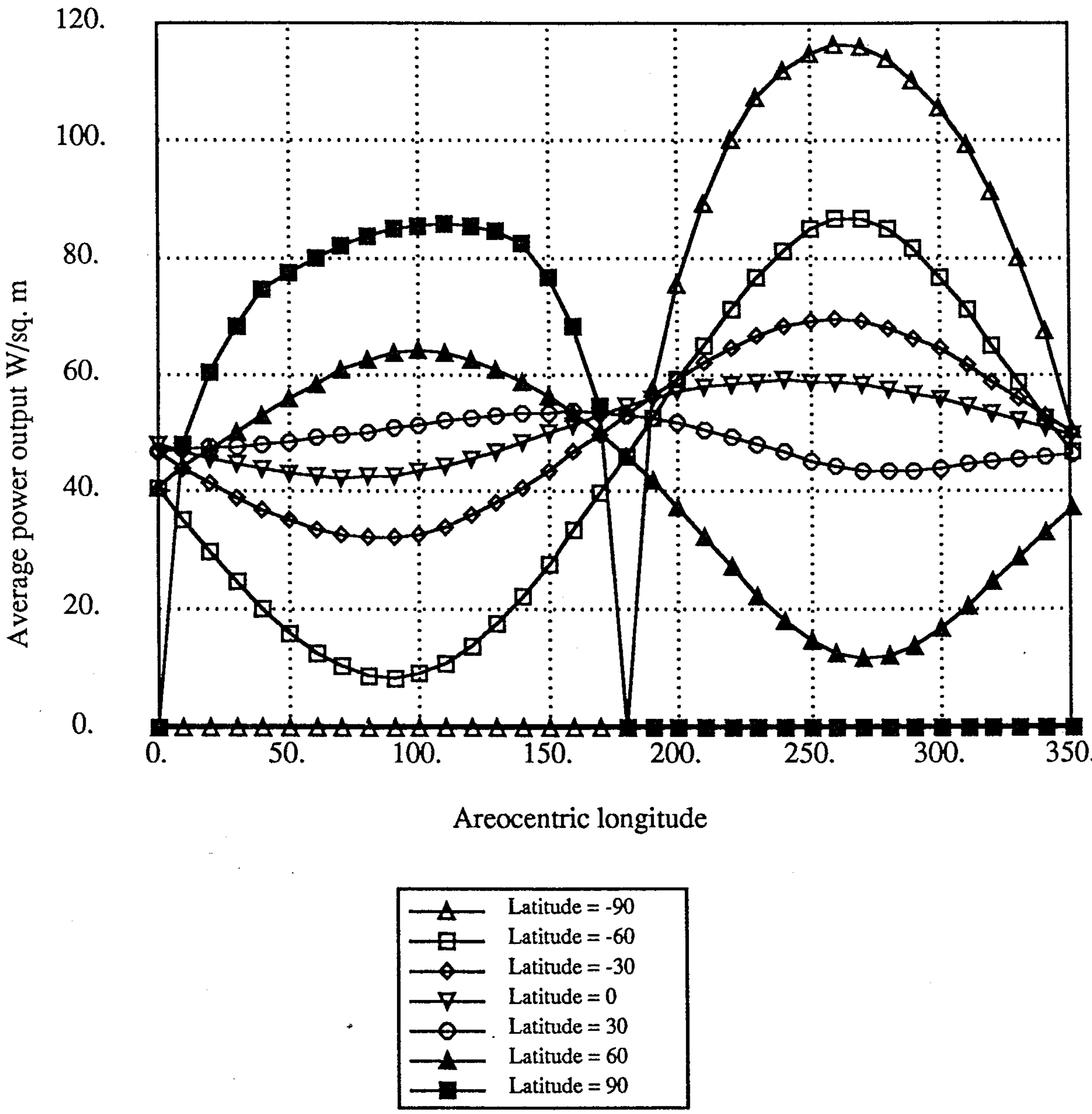

Figure 3-5. Solar panel average power output for a tracking, horizontal GaAs panel with a optical depth of 0.5.

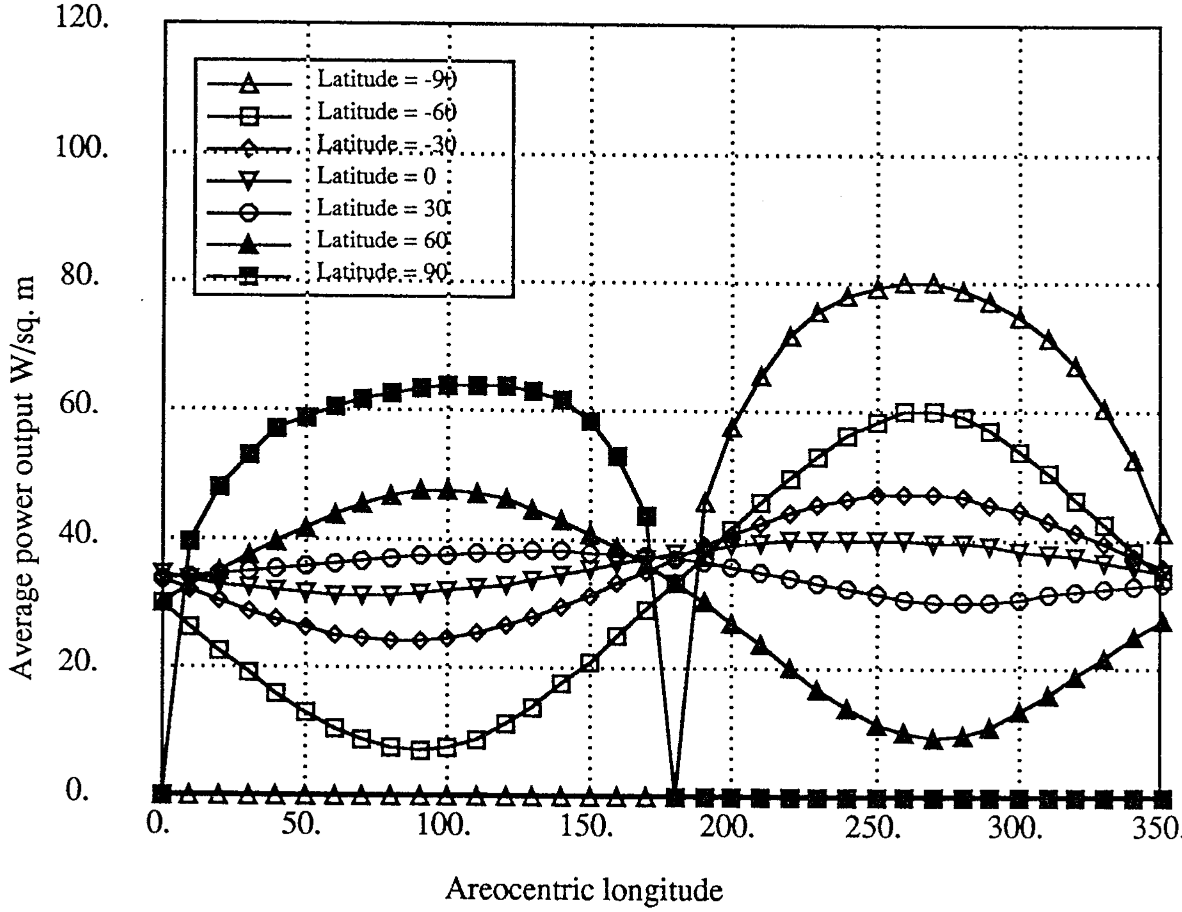

Figure 3-6. Solar panel average power output for a tracking Silicon panel with a optical depth of 0.5.

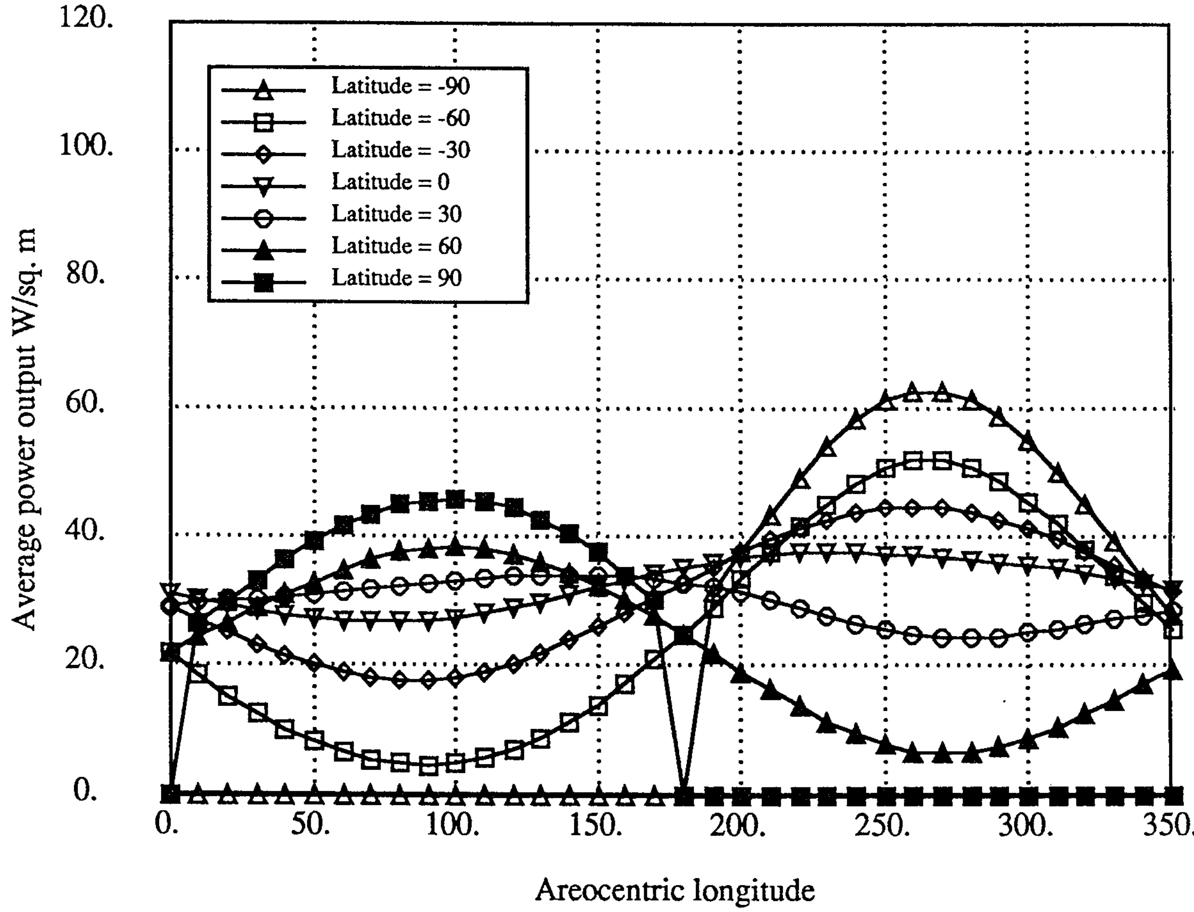

Figure 3-7. Solar panel average power output for a tracking GaAs panel with a optical depth of 2.0.

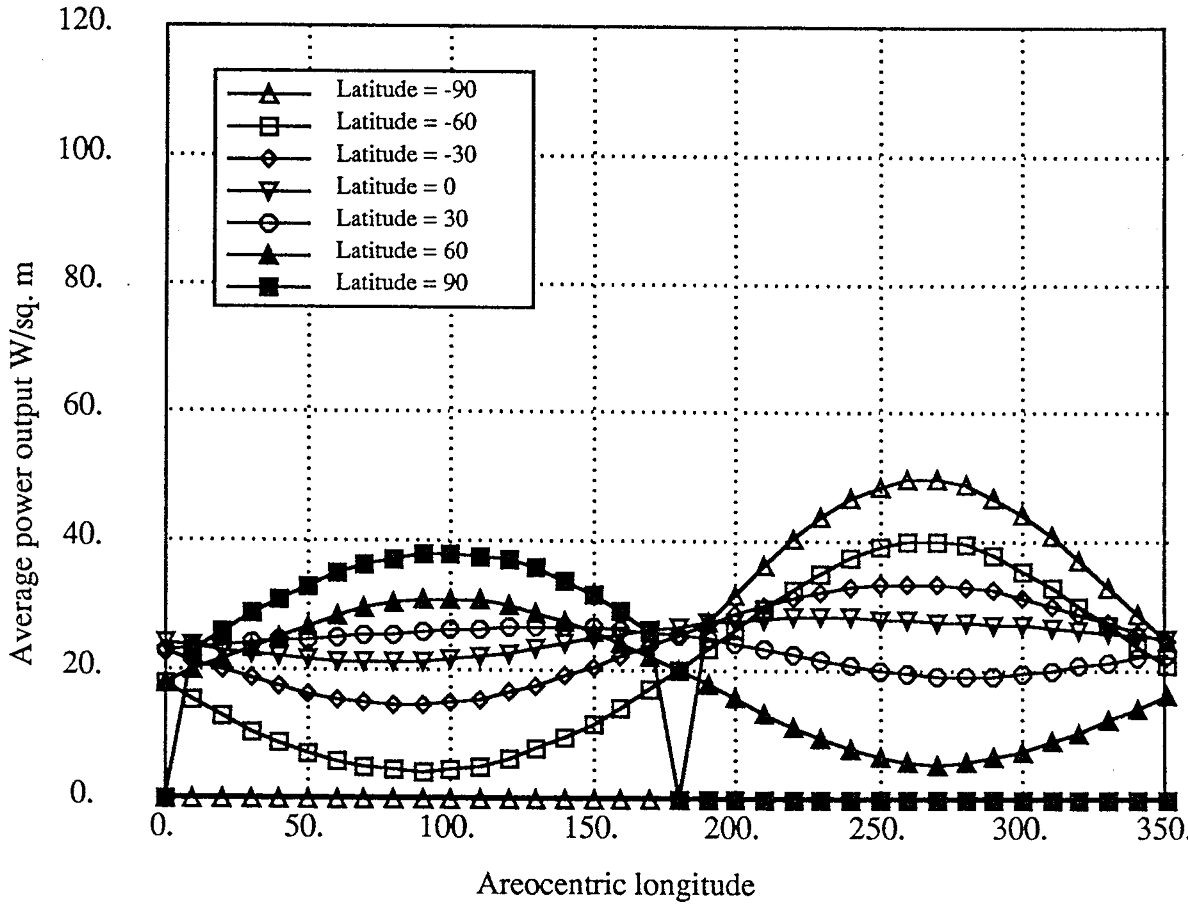

Figure 3-8. Solar panel average power output for a tracking Silicon panel with a optical depth of 2.0.

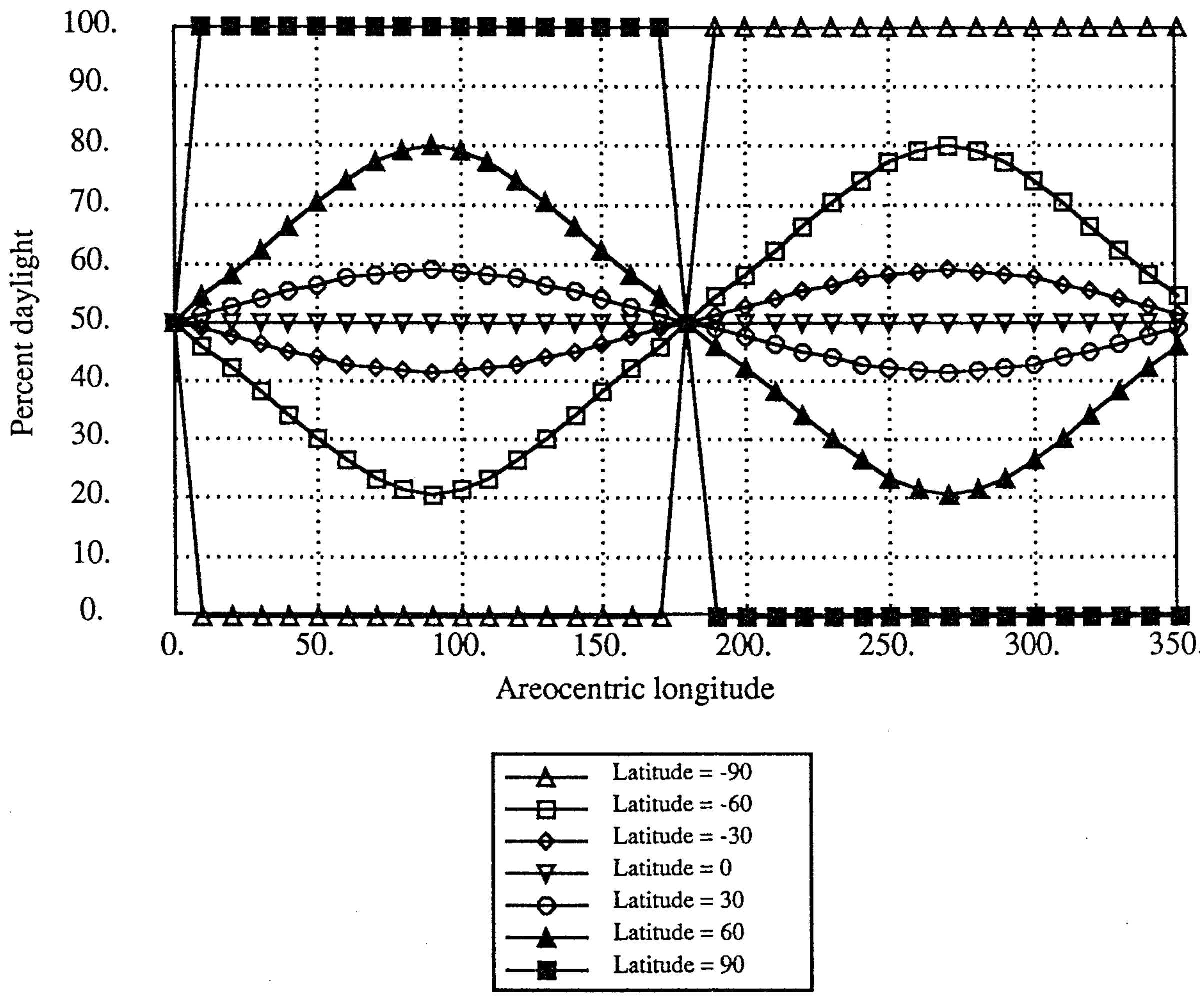

Figure 3-9. Percent of daylight per sol

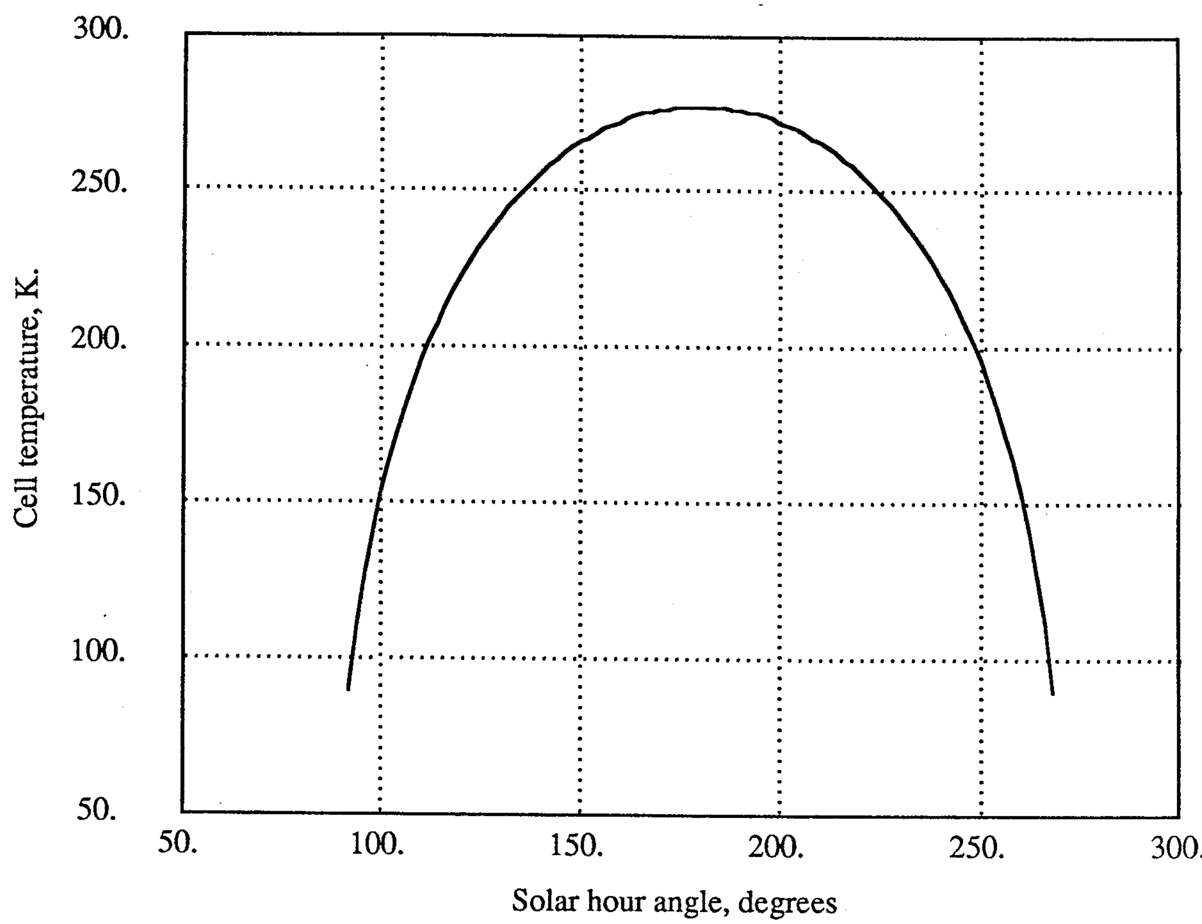

Figure 3-10. Cell temperature for the nontracking Gallium panel, areocentric longitude of 0 deg., latitude of 30 deg., optical depth of 0.5.

functions of the wavelength of the light. This results in errors in both the tracking and horizontal collector results. The degree that this effects the energy calculations is not known, of even if it results in a increase of reduction in energy.

At present, the location on Mars and the time of year when the rover will be operating is not certain. Thus there is a wide range of average power output per square meter values that be used in the design process. Consideration of all possible power levels will complicate the design process, which at the level of analysis of this study is undesirable. Thus, a single representative value will be used for each cell type. The average power output of a GaAs panel is 22 watts per square meter or more for a wide range of latitudes and areocentric longitudes. If the rover is designed for this power level, then most of Mars will be accessible to it. The equatorial region between about –20° to 20° will be accessible the entire year, making this area appropriate for extended missions. Regions further north or south are suitable for missions of limited duration. For silicon cells, a value of 17 w/m^2 will be used.

Section 4
SOLAR THERMAL ENERGY COLLECTION

4.1 Problem Description

The Mars environment is cold, with average temperatures of 210 K, dropping as low as 150 K. Any Mars rover must be able to cope with this environment. This generally requires that the rover have a thermal control system to provide heat to various systems as needed. For the designs with the primary electrical power coming from a radioisotope thermoelectric generator (RTG), the thermal control system would rely on electric power, or from small radioisotope thermoelectric heaters (RTHs).

Both RTGs and RTHs require the use of plutonium. The main reason for examining the possibility of a solar-powered rover is to eliminate plutonium. The use of solar cells for electric power eliminates the need for the RTG; however, the thermal control task remains. The most obvious way to handle it is to use electrical power from the solar panel. The power needed is quite large: for example, the current MRSR design uses 50 watts for thermal control. If this is to be supplied by solar cells, a panel with an area of 2.5 to 3 square meters will be needed for this task alone. This is based on the average power output value given in Section 3, making some allowance for storage losses.

Another way to get the energy needed is with solar thermal collectors. This has the advantage that the efficiency of solar thermal collectors is potentially much higher than the 20 percent or so that can be achieved with photovoltaics. Also, the energy can be stored as either sensible heat or latent heat. In both cases, water would make a good storage medium. Water can store 64 watt hours per kilogram in the phase change from solid to liquid, and an additional 1.16 watt hours per kilogram per degree of temperature change.

4.2 Collector Design and Analysis

Solar thermal collectors need to maximize heat absorption and minimize heat loss. One common method for doing so uses a special coating, called a selective surface, on the absorber that enhances absorption of solar radiation while reducing the radiation of long wave infrared. Also used are cover windows to reduce the loss due to conduction and convection to the air, and to some extent, the loss of heat due to infrared radiation. The windows can also be coated with a selective surface on the inside that is transparent to solar radiation but reflects thermal infrared emitted by the collector back to the absorber. The shape of the collector is usually either flat or cylindrical.

In designing a solar thermal collector for use on a Mars rover there are several factors to consider. As the collectors are supplying heat to the thermal control system, the temperature that must be maintained by that system will have a large effect on the performance of the collector system. Generally, the lower the temperature that must be maintained, the higher the efficiency of the collector. The complexity of the system also needs to be minimized so as to reduce the chance of failure. In addition, there are constraints of size and shape imposed on the collector by the design and operation of the rover.

There are two main loss mechanisms for the solar collector. The first is radiation loss. This is proportional to the temperature to the fourth power and is also a function of the surface emittance. Some materials have a very low emittance, 10 percent or less of that of the ideal black body. The other main loss term is loss to the air by conduction and convection. This loss can be estimated using the Welty equation as given in Meinel (1976):

$$H = 0.062\ k\ Re^{0.62} / L$$

where k is the thermal conductivity of the air, L is the length of the surface losing the heat, and Re is the Reynolds number of the surface:

$$Re = \rho\ V L / \upsilon$$

based on its length, L, the wind speed (V), the density of the air (ρ) and the viscosity (υ).

For typical Martian conditions and a carbon dioxide atmosphere we have;

$\rho = 0.020$ kg/m^3

$k = 0.0226$ W/m/K

$\upsilon = 1.07 \cdot 10^{-5}$ kg/m sec

$V = 3$ m/sec

$L = 2.5$ m

which gives $H = 0.21$ W/m^2/K. This is the combined loss due to both conduction and convection to the air. Note that it is a small loss, even if the temperature of the solar collector is 100 degrees greater than that of the air, the loss of heat is only 21 watts per square meter. By comparison black body radiation from a surface at 0° C is 315 watts per square meter.

In order to determine the amount of heat lost by convection and conduction, the temperature difference between the air and the collector must be known. The temperature of the collector will be assumed to be equal to that of the thermal storage module, as would be expected with good thermal contact between the two. Data from the Viking landers were used to find the daily maximum and minimum air temperature as a function of season. The diurnal temperature variation between the maximum and minimum was assumed to vary sinusoidally. This model was used for all calculations presented here, at all Martian latitudes. This is not very realistic for latitudes other than that of the Viking lander, but the resulting errors are expected to be small, as most of the heat loss is by radiation.

The large difference between the convective and radiative loss terms indicates that controlling the convective loss by use of cover glasses may not be necessary, a bare collector can be used. Controlling the radiative loss can be done effectively with selective surfaces.

The relative merit of a selective surface is best described by its selectivity ratio, the ratio of its absorption of solar energy to its emission of infrared in the frequencies appropriate to the temperature at which the surface is operating. Selectivities of 10 can be achieved with coatings that are sufficiently low in cost that they are used for commercial solar collectors. Selectivities of 50 are possible with higher cost coatings. For the Mars rover, the coating must not only have a high selectivity, but must be able to withstand the Martian environment. This includes dust, low temperatures, high levels of ultraviolet, and weathering from the atmosphere. Due to the need for surviving the Martian environment, a selectivity of 10 will be assumed to be the best that can be obtained.

A thermal control system based on solar energy requires a thermal storage module. This can be connected to the collectors in one of two ways. It can be directly connected to the collector in such a manner that heat can flow either from or to storage. This results in stored heat being lost during periods of darkness. The other option is to place a "thermal diode" between the collector and the heat storage module. Such a thermal diode could be simply a pair of temperature sensors and a pump that circulates a heat transfer fluid through the collector and the store, or something more advanced. This will result in reduced heat loss at the cost of increased complexity.

4.3 Results

The average thermal power that can be collected on Mars was found for several cases. For all cases, the collector configuration was a flat plate oriented horizontally with no cover glasses. A selective surface as described above was assumed. Water was used for the thermal storage medium, with the phase change from solid to liquid at 0° C being used to store the heat. This should be warm enough for the equipment that must heated.

The four cases analyzed were with and without the thermal diode and for atmospheric optical depth of 0.5 and 2.0. For each case, results were found for several latitudes and areocentric longitudes. The results, in terms of thermal power collected averaged over a sol are shown in figures 4-1 to 4–4. Several interesting trends are shown. The average thermal power that can be collected is 60 to 80 w/m^2 for a large portion of the surface and seasons. The benefit of the thermal diode is to increase the energy collected by 25 to 30 w/m^2, depending on the season and location. Comparing the actual energy collected to the energy available shows that the collector operates at an efficiency of about 80 percent for the case with the thermal diode, dropping to 60 percent for the case without the thermal diode. This compares favorably with the 20 percent efficiency available with solar cells. The high efficiency also indicates that there is little to be gained by using a more complex collector design with cover glasses, selective windows, and so on. A bare collector is sufficient.

The effectiveness of such a simple collector design suggests an interesting possibility. The entire rover could be covered with a selective surface. This would make the rover a large solar collector, and the rover mass would become the thermal storage module. This could greatly simplify the thermal control of the rover.

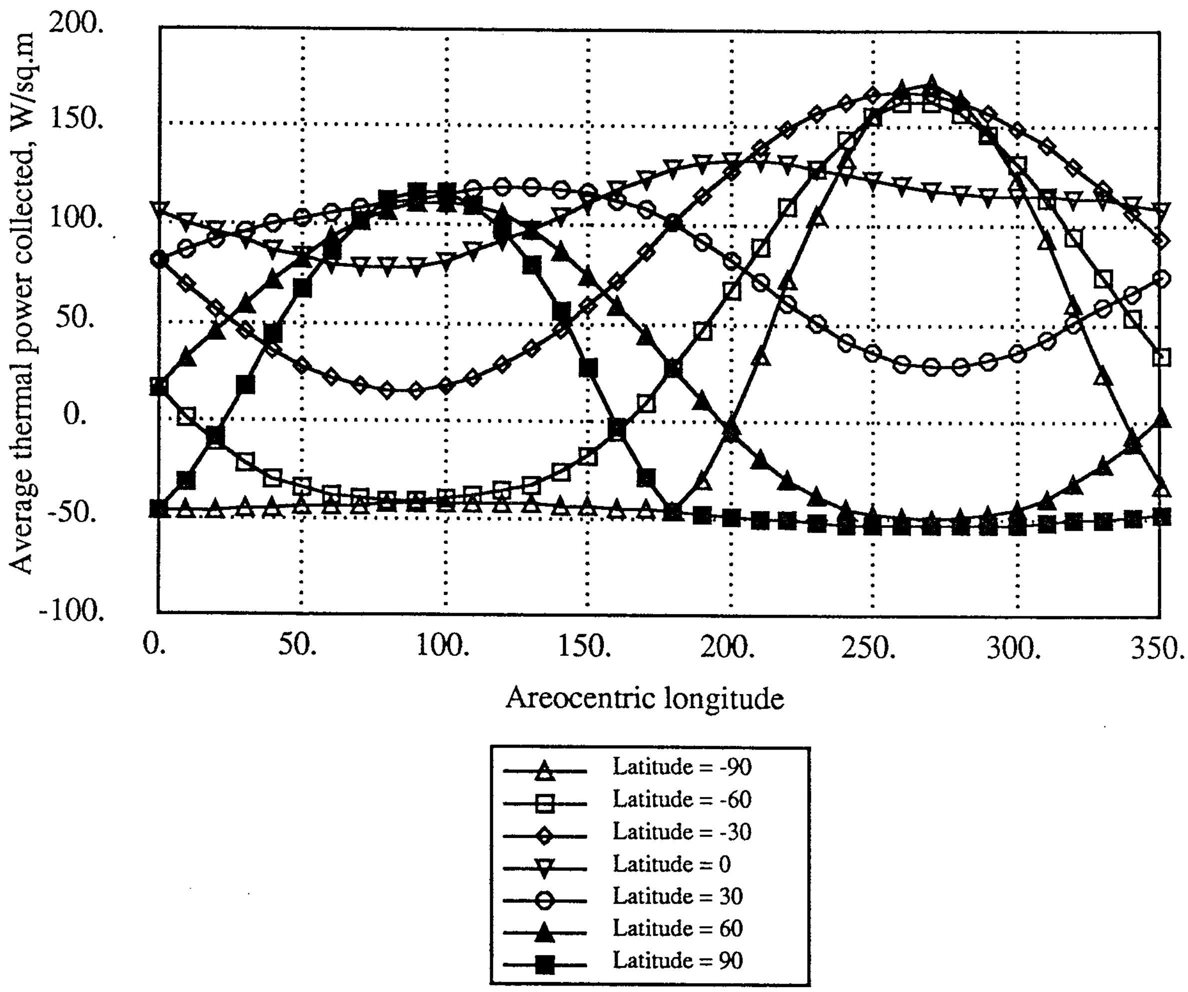

Figure 4-1. Solar thermal power collected for a horizontal absorber, selectivity = 10, wind speed = 3 m/sec, optical depth = 0.5, no thermal diode. Absorber tempreature = 273 K.

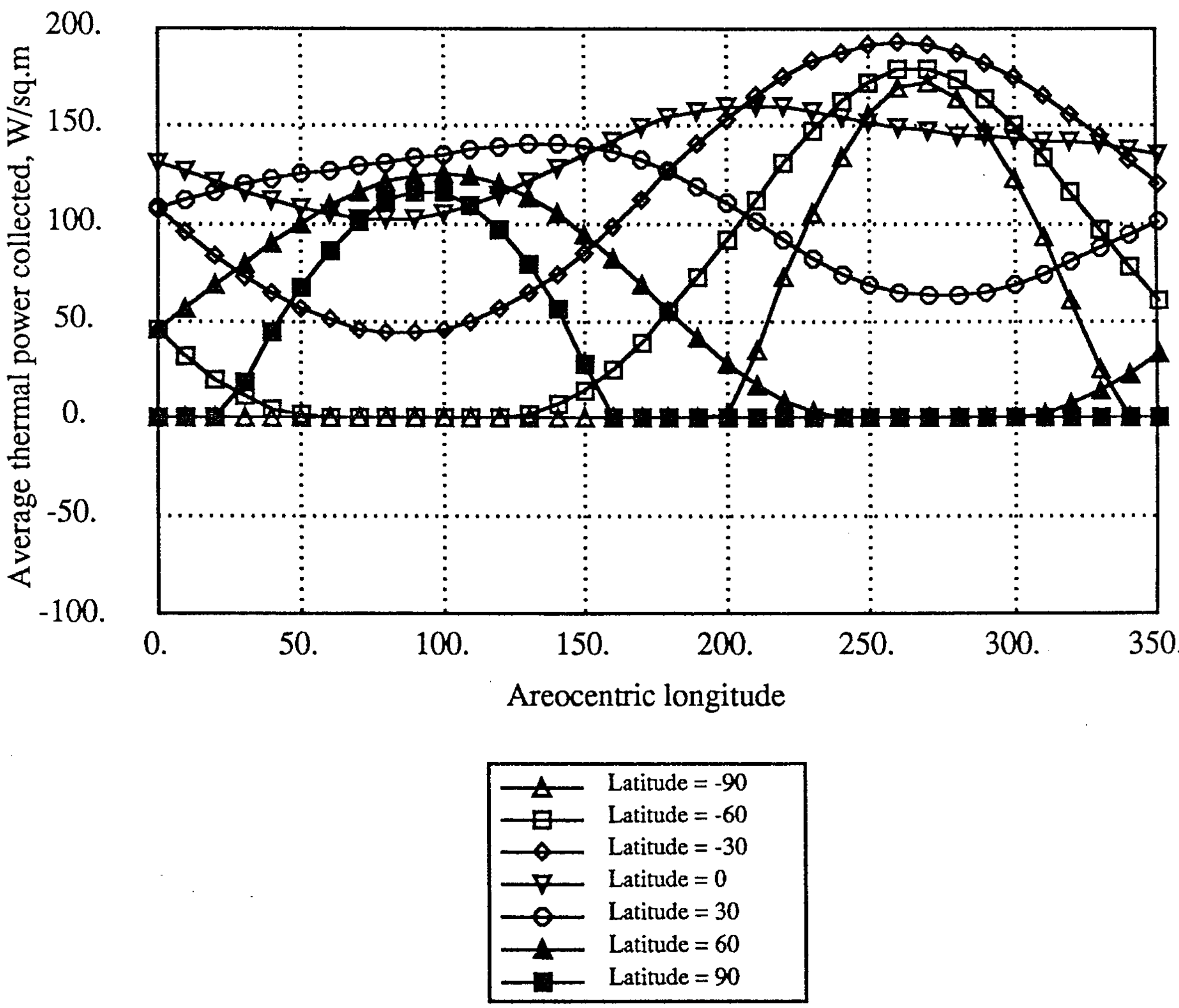

Figure 4-2. Solar thermal power collected for a horizontal absorber, selectivity = 10, wind speed = 3 m/sec, optical depth = 0.5, with thermal diode. Absorber tempreature = 273 K.

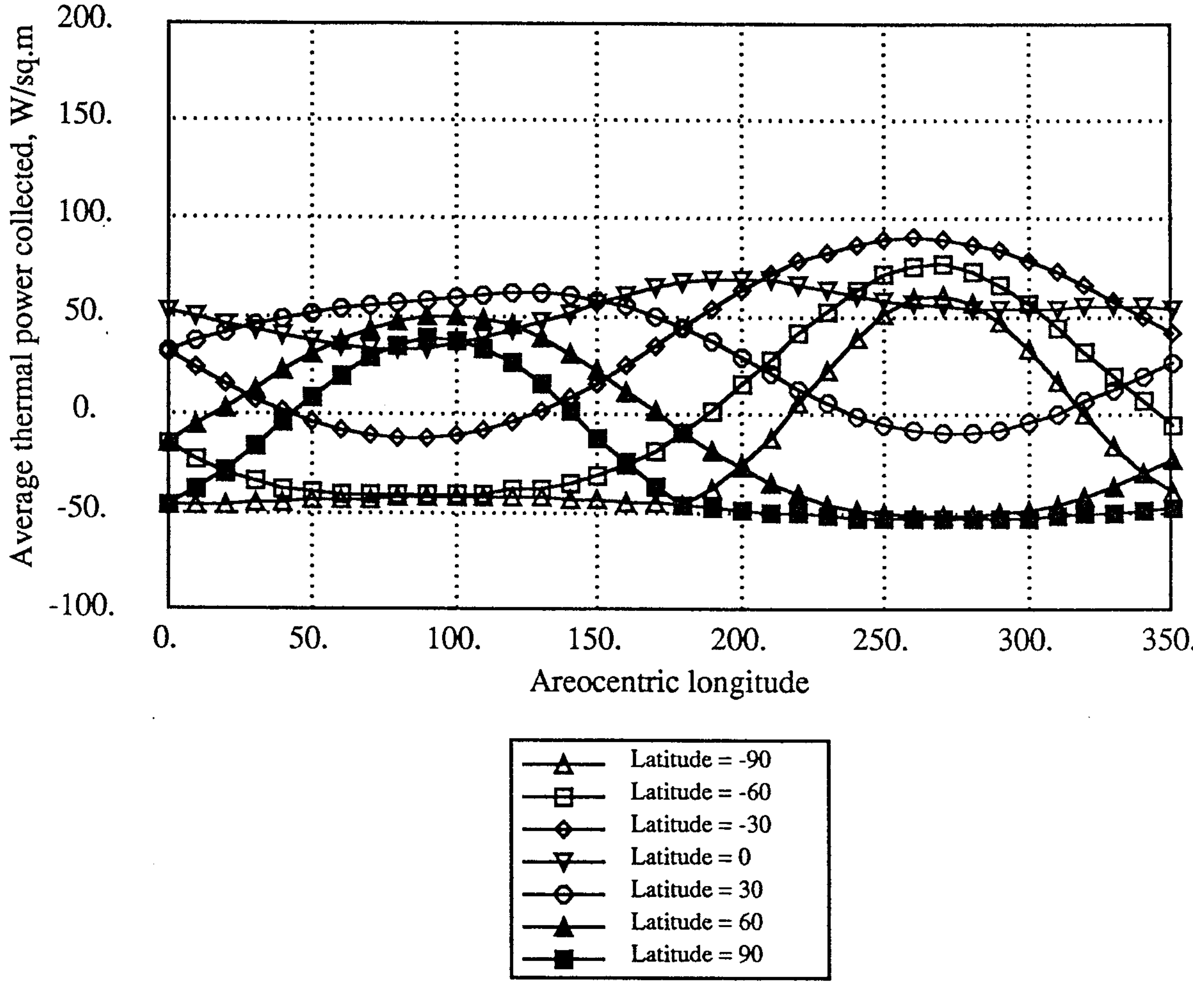

Figure 4-3. Solar thermal power collected for a horizontal absorber, selectivity = 10, wind speed = 3 m/sec, optical depth = 2.0, no thermal diode. Absorber tempreature = 273 K.

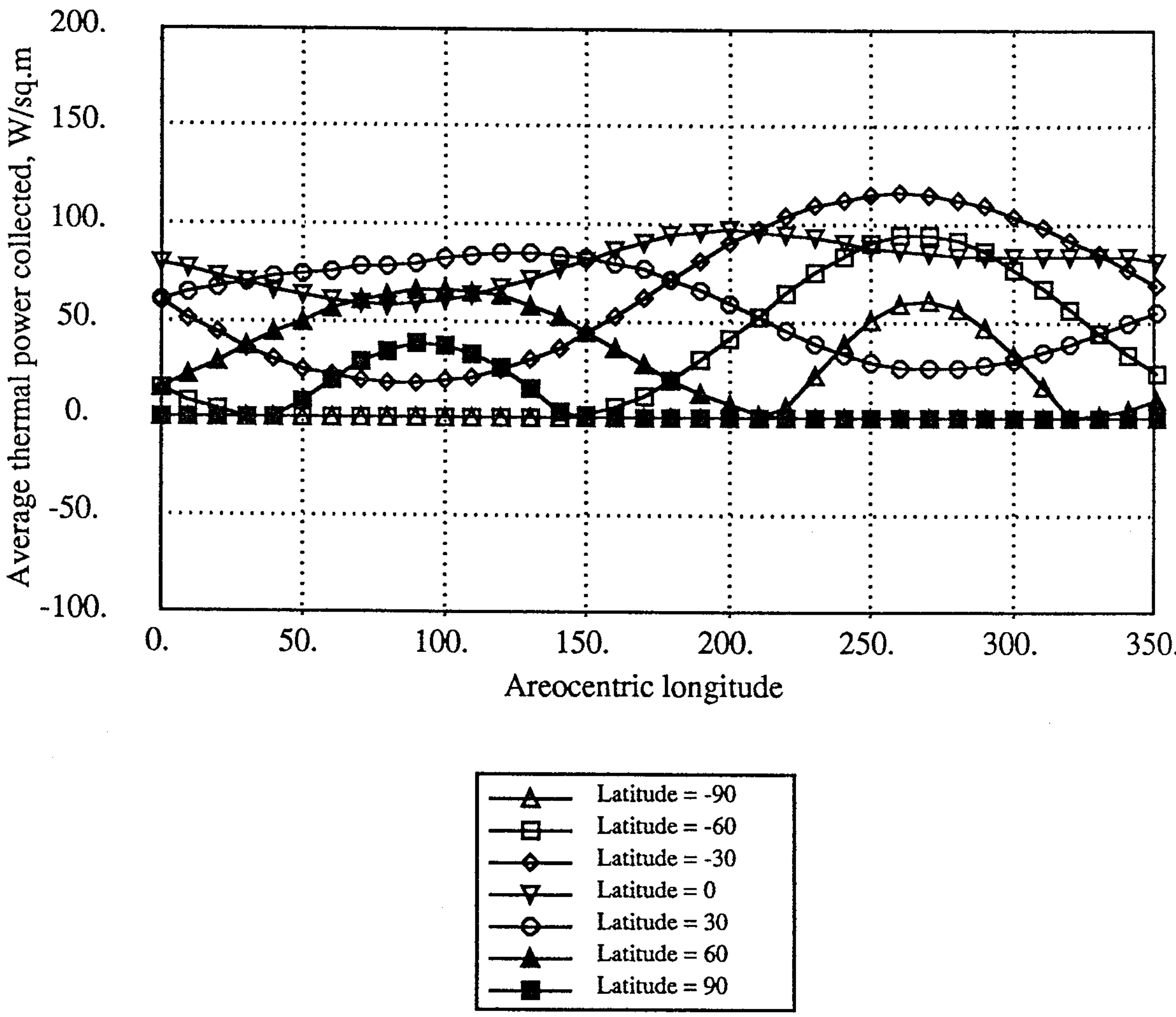

Figure 4-4. Solar thermal power collected for a horizontal absorber, selectivity = 10, wind speed = 3 m/sec, optical depth = 2.0, with thermal diode. Absorber tempreature = 273 K.

Section 5
POWER REQUIREMENTS

5.1 Assumptions

The power needs of the rover have been assumed to be similar to those of the MRSR vehicle. This vehicle has several operating modes during which each of its systems requires a particular amount of power. If each of these power requirements is known, and an operational scenario is known, then the average power needed by the vehicle can be determined.

In the following sections, the power needs of the MRSR vehicle systems will be examined, starting with the mobility system, then the thermal control system and, finally, the remaining systems. Next, the impact of these needs on the average power use by the vehicle will be determined.

5.2 Mobility Power Needs

Normally, the resistance to vehicle motion is due to three components, namely: air, traction and gradients. For a Mars rover, the air resistance is negligible due to the low rover speeds (< 1 m/s) and low atmospheric density (~1 percent of Earth's). The traction resistance is the energy lost due to deformations of the wheels and the surface on which the wheels are rolling and also energy lost in wheel bearings and seals. Values for the rolling resistance are normally given as some percentage of the vehicle weight, but reliable values are difficult to obtain. In the case of a Mars rover, where the construction details as well as the Martian surface characteristics are unknown, it is impossible to estimate with confidence a value for the rolling resistance. The rover will probably have to operate on surfaces ranging from loose sand to rocky terrain. Common sources on rolling resistance (Mark's Mechanical Engineering Handbook, eighth edition, 1979) give a range of 0.15 to 0.30 for a pneumatic tire on loose sand and 0.1 for badly cobbled roads. Because of the uncertainty in the expected value of the rolling resistance, in this report we shall use the range of 0.15 to 0.30 as representative of what may be expected for the rover operation on the Martian surface.

The power to overcome rolling resistance is then estimated from:

$$P_T = C_T\, W\, V/\eta_D$$

where: P_r = power to overcome rolling resistance (watts)
C_r = coefficient of rolling resistance (0.15 - 0.30)
W = vehicle weight (newtons)
V = vehicle speed (m/s)
η_D = drive efficiency (0.5 - 0.8).

The drive efficiency as used here is the ratio of the power available at the wheel axle to the output power at the array. This efficiency then includes the efficiencies of the electronics between the array and the motor, of the motor itself, and of the gearbox. The GM Sunraycer, a solar powered electrically driven terrestrial four wheeled vehicle developed by AeroVironment for General motors achieved drive efficiencies of about 85 percent (Sturtevant, 1989). This efficiency will be unlikely on Mars because of the large gear reduction required between the motor and the wheels, and the low temperatures. The vehicle will be operating at very low temperatures (~ 200 K), so seals and lubrication will make an unknown contribution to the total rolling resistance.

Harmonic and planetary gear systems are under consideration for the final drive. The planetary gearbox is heavier than the harmonic gear system, but has potentially high efficiency (>90 percent) instead of the lower efficiency harmonic drive (efficiency ~ 50 percent or less under partial load conditions). How these would be lubricated and sealed for the lower Mars temperatures is undecided. Because of these unknowns, we have again assumed a range for the value of the drive efficiency. As an upper bound, we have chosen 80 percent, in keeping with Sunraycer experience, and as a lower bound 50 percent.

Slope or gradient resistance is usually given as the product of the grade in percent times the vehicle weight. If a 30° slope is chosen as the maximum, then the additional resistance is one half the vehicle weight. This is somewhat misleading because there will be a weight transfer to the rear wheels when climbing a slope that may influence the rolling resistance on those two wheels, particularly on soft surfaces. Another consideration in estimating the required drive power is the necessity of overcoming a large obstacle that cannot be avoided. The power needed to climb a slope is recovered when the rover descends. If the rover always returns to its starting point, the net energy needed to climb slopes is to the first approximation zero. However, the different operating conditions caused by slopes will result in added inefficiencies in the drive system, increasing the average power needs.

Estimates of the power required to overcome slopes and obstacles depend on the occurrence of these in the terrain and also on the geometry of the rover. The emphasis in this report will be on estimating the average power requirements for sizing panel arrays. Further information is required to estimate the additional power necessary to overcome slopes and obstacles.

• **Drive power estimates**

In Figure 5-1, estimates of the power required for the rover to operate on level ground with a rolling resistance coefficient of 0.15 and a drive efficiency of 0.5 are shown for various rover masses. It is clear from the figure that a light rover, or a slow one, will require less power. The power values in this figure are those required when the rover is in motion. For sizing of photovoltaics panel, it is more useful to have this information in terms of power averaged over the entire day. This has been done in Figure 5-2, which shows that the power requirements are quite modest. For example, at an average speed of 1 km/sol, the power required for a 500 kg rover is about 6 watts.

Based on average power required, it might be suggested that the rover mass is not a significant factor. However, Figure 5-1 shows that the heavier rovers require large instantaneous power inputs to move and particularly to overcome obstacles. This would require larger, heavier motors. For a photovoltaic power system, it is essential to maintain low power requirements and hence the emphasis in rover design should be to produce as light a rover as possible. This will assist in launch vehicle payload constraints as well.

Figures 5-3 and 5-4 show the influence of the value of the rolling resistance on the drive power requirement. To keep the power requirement low, it is desirable to have as low a rolling resistance as possible. The coefficient of rolling resistance depends primarily on the deformations of the wheels and ground. To keep the rolling resistance low in soft materials, the contact pressures must be low. This is normally done by using wheels that have a large contact patch. By reducing the weight of the rover for a given wheel size, the contact pressure can be reduced. In this case, reducing the rover weight has a two-fold effect on the rolling resistance. By decreasing the weight, the rolling resistance decreases and, if the contact patch area is maintained, the coefficient of rolling resistance will also decrease.

Figures 5-5 and 5-6 show the instantaneous and averaged power requirements for the range of values of the drive efficiency. For a low required power, the drive efficiency must be high. As demonstrated by the GM Sunraycer, the drive system can be made to have an efficiency of about 85 percent. The gearbox can be made efficient and light by choosing a planetary gear train and tailoring each stage.

Although the above examination of the rover drive power requirements is incomplete because power for slopes and obstacles has not been included, a major conclusion that can be drawn from

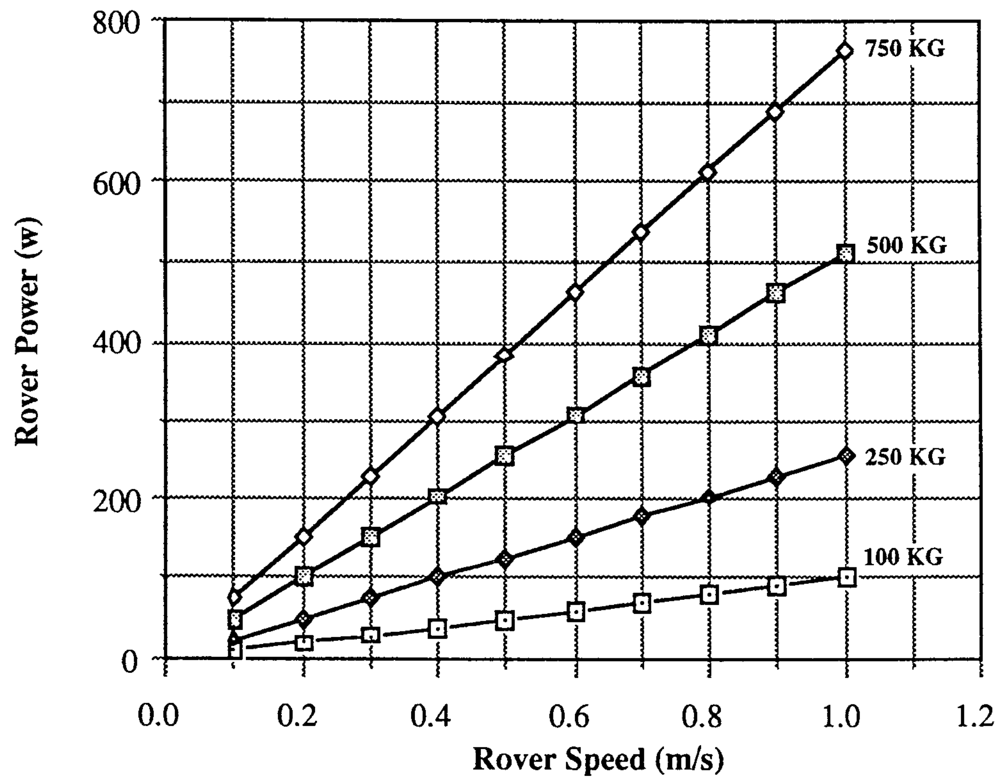

Figure 5-1. The estimated rover drive power for various speeds and masses. The coefficient of rolling resistance is 0.15 and the drive efficiency is 0.5.

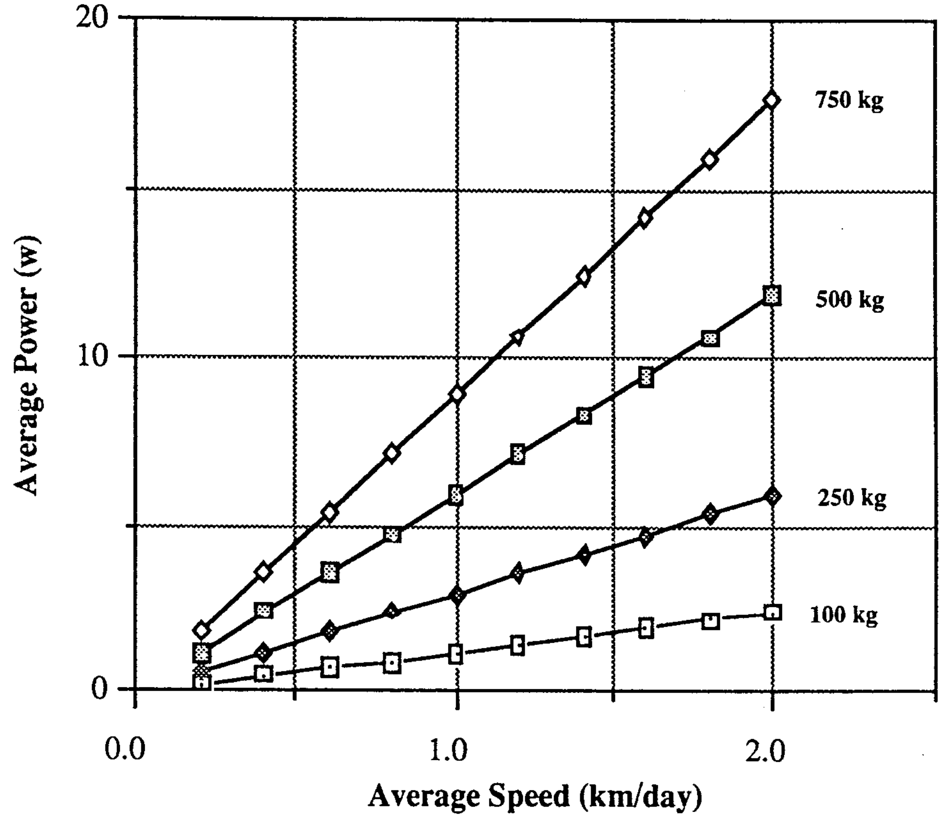

Figure 5-2. The estimated drive power averaged over the number of kilometers traveled in one Martian day.

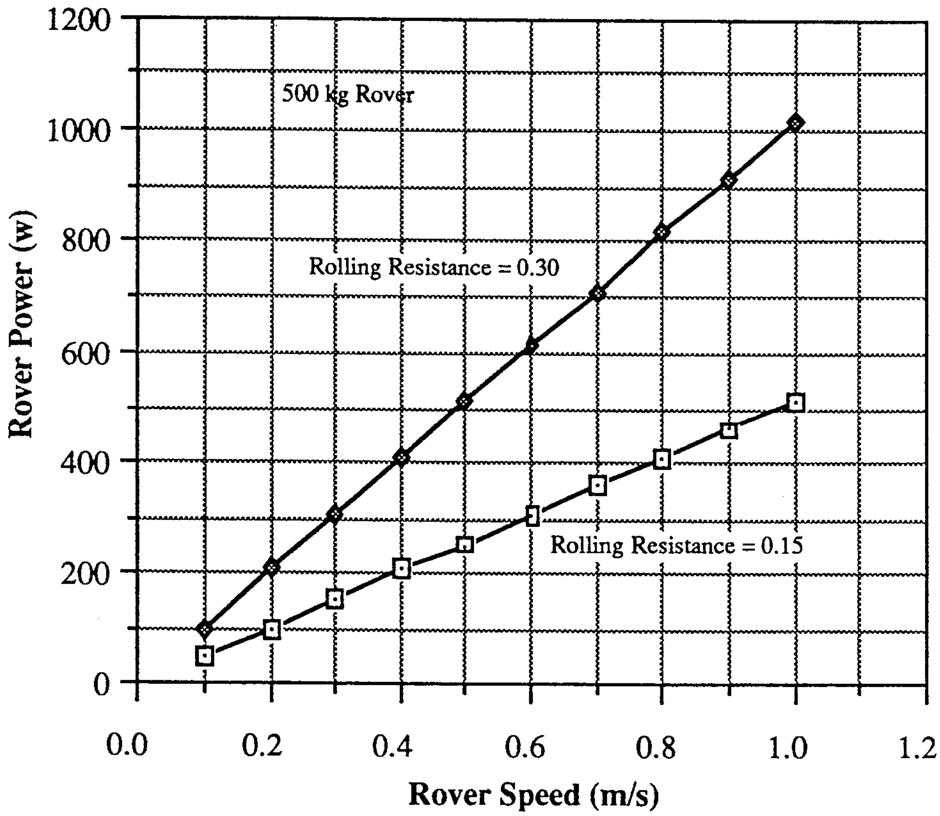

Figure 5-3. The estimated rover drive power for a 500 kg rover with a drive efficiency of 0.5 for two values of the rolling resistance coefficient.

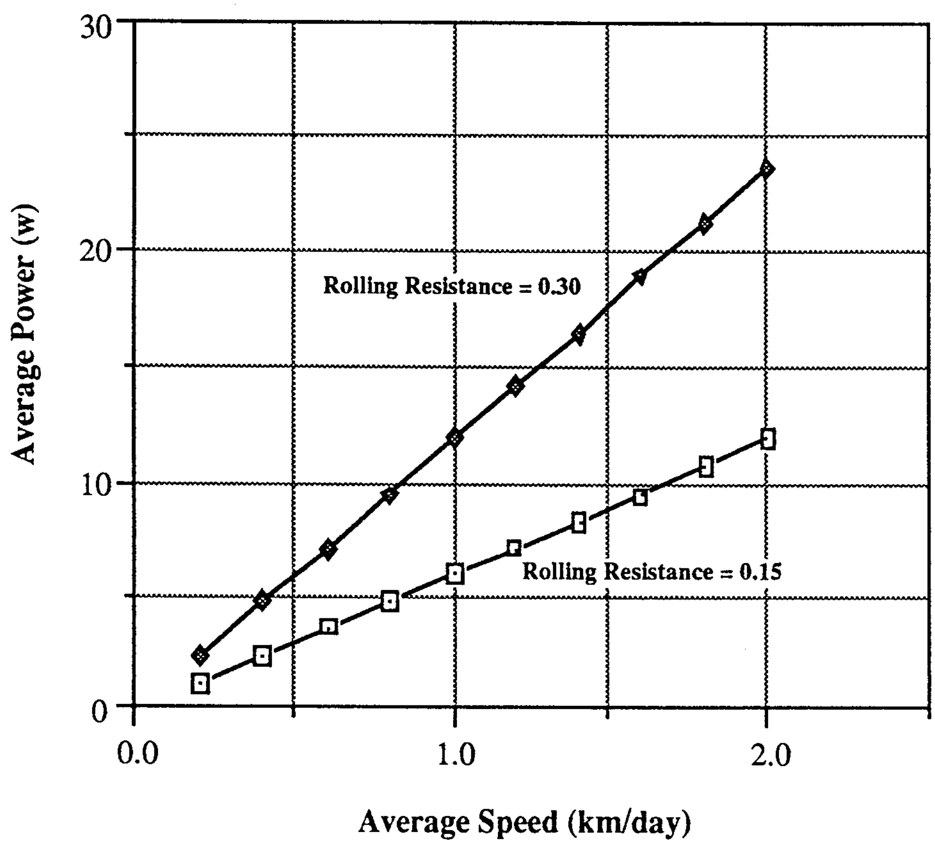

Figure 5-4. The estimated drive power averaged over the number of kilometers traveled in one Martian day. Rover mass is 500 kg and the drive efficiency is 0.5.

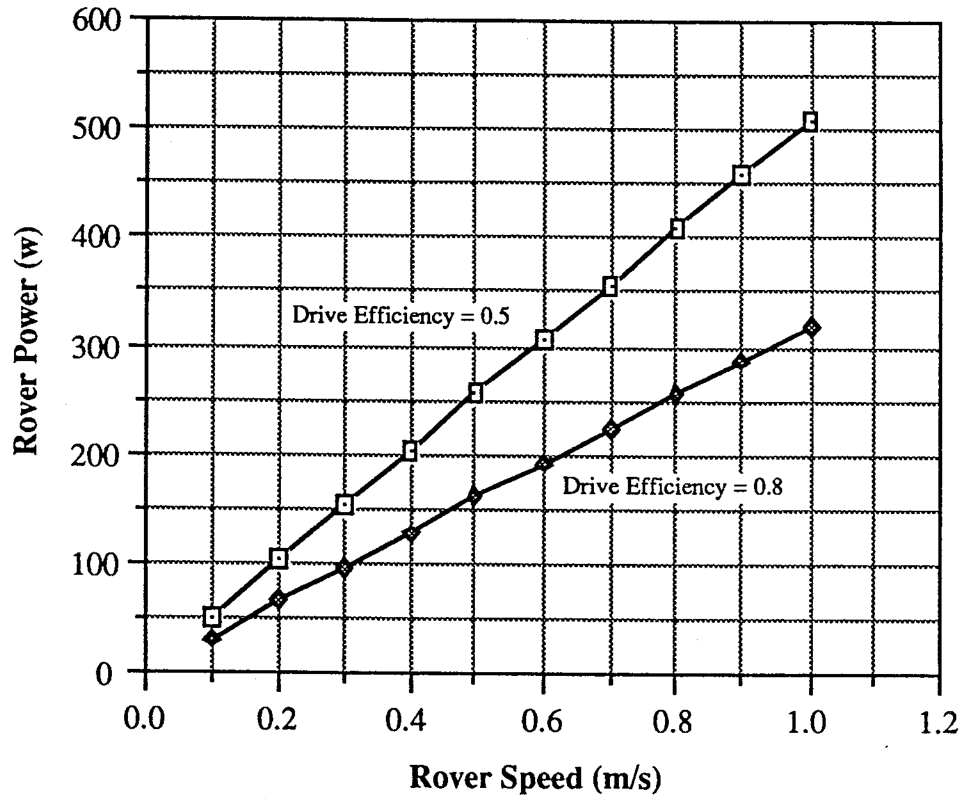

Figure 5.5. The influence of drive efficiency of the estimated rover power for a 500 kg rover and a rolling resistance of 0.15.

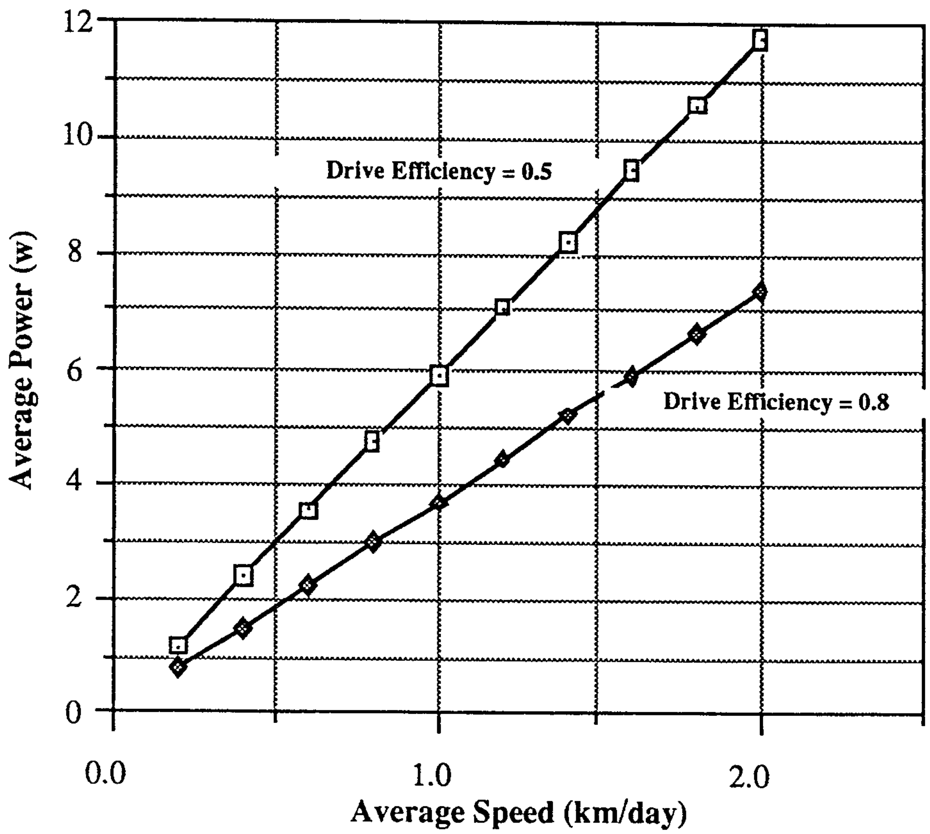

Figure 5-6. The influence of drive efficiency on average rover power. Rover mass is 500 kg and the assumed coefficient of rolling efficiency is 0.15

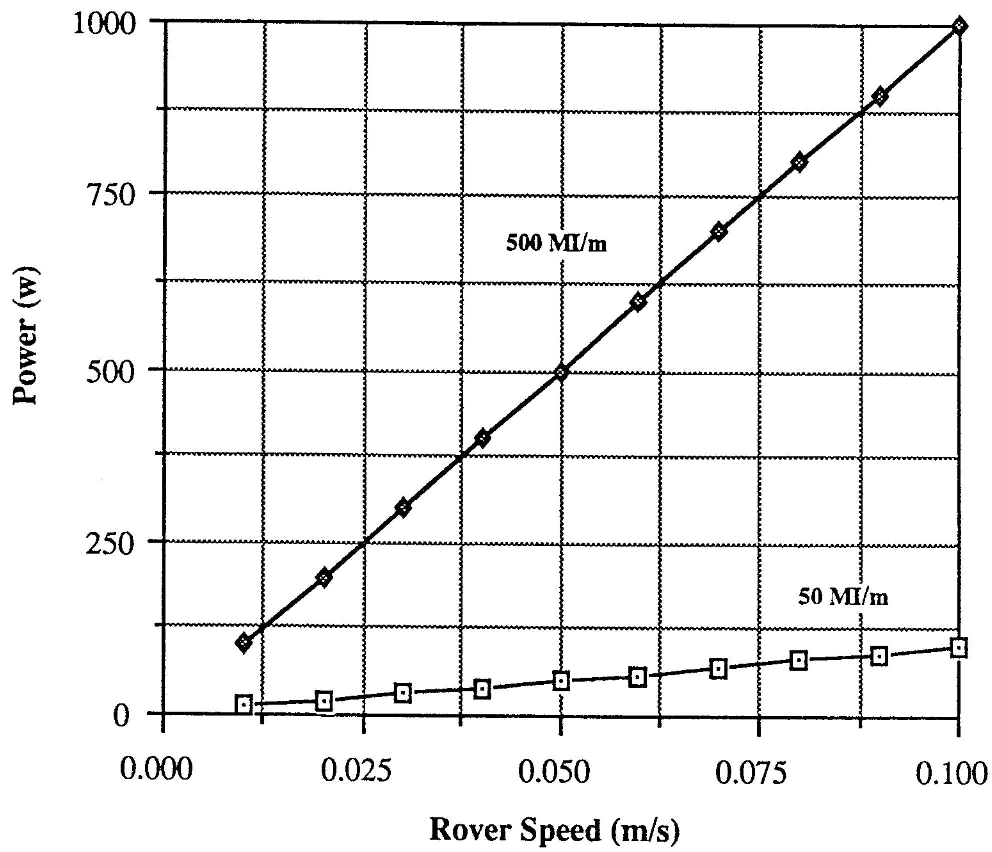

Figure 5-7. The estimated power for navigation at 20 watts/MIPS.

the study is that it is necessary to keep the rover as light as possible.

• **Rover Speed**

In the previous section it was noted that the slower the rover moved the better from the point of view of the drive power. It is worthwhile examining the rover speed for a few moments to determine what the constraints on this variable are.

During the Mars mission it is desirable to have the rover visit as many geologically diverse regions as possible. Since the mission has a limited duration, this means the rover's average speed should be high. The average speed is controlled primarily by the navigation method. There are two possible methods for the local navigation: computer-aided remote driving (CARD) and semi-autonomous navigation (SAN). With the CARD approach, stereo pictures from the rover are uplinked to Earth, where a human operator views the image on a three-dimensional display. The operator then plots a path and downlinks instructions to the rover. With this arrangement, rover steps of 10 - 20 meters are possible. However, because of the long time delay (~30 minutes) due to signal transmission at speed the of light, and the limited Earth view time (~10 hours), only about 20 steps or 200 - 400 meters would be possible per Martian day. Since the rover spends most of its time waiting for instructions, there is no advantage for the rover in moving fast and a slow speed is acceptable. The CARD approach is suitable for a mission with a limited range or a long duration.

In the semi-autonomous approach, the rover moves by comparing images and/or range information with a map uplinked from Earth that has been prepared from orbiter pictures. In this scenario, the rover may navigate several kilometers without intervention from a human operator. Because real time Earth control is not needed, the signal delay is not of concern. In this case, speed is limited by the computational power on board the rover. Current SAN software require 50 to 500 million instructions per meter of travel (Wilcox et al., 1988), although reduction to 10 million is possible. To travel at 10 cm/sec then requires a computational capability of 5 to 50 million instructions per second (MIPS). In this case, the only limit on the speed is imposed by the on-board computational capacity.

If the rover used SAN and sufficient computational capacity was available, would there be any advantage to traveling fast? If the geological areas of interest are separated by a large distance, and they are all to be visited in a short time, then the answer to this question is yes. The rover would travel quickly between the areas and then spend time studying the areas of interest. There would then be a definite need for the development of space-certified computers capable of carrying out many operations per second.

In addition, there is some advantage for increased speed during the move itself even with a fixed computational capability. The rover operates in a cyclic manner with the first part of the cycle being computational, planning the move, the later part being mechanically executing the move. During the computation part of the cycle in which it finds how to do the next move, the rover does not move. During the movement part, it does not compute for the subsequent move. The two parts of the cycle do not overlap. Thus, increasing the speed of either will increase the distance traveled per unit time. While in transit mode, the rover may spend 70 percent of its time computing and the rest actually moving. If the movement speed was increased by a factor of two, then the distance traveled per unit time would be increased by 18 percent. On a mission where 200 kilometers of movement is to be accomplished, this would add 36 kilometers to the rover's capability.

• **Navigation computation requirements**

At the present level of development, SAN requires 50 - 500 million instructions per meter of travel. The estimate for the power required to perform this number of instructions is currently not well determined. For example, Wilcox provides the following power requirements for on–board computer performance for a number of missions:

Estimated Power/MIPS

Mission	Power, watts
Galileo	200
CRAF*	20
MAX**	5
MAX with Image processing+	3

*Comet Rendezvous Asteroid Flyby

**A multiprocessor, data flow computer, assumed for the MRSR Phase 1 design

+MAX with VLSI-based image processor.

The power required for navigation is given by:

$$P_N = V\ N\ W_m$$

where: V = rover speed (m/s)

N = number of instructions required per meter of travel

W_m = power required per million instructions per second (watts).

This power requirement has been plotted in Figures 5-7 and 5-8 for instantaneous power and average power. It has been assumed in these calculations that the computational requirement is 20 W/MIPS. In Figure 5-7 the navigation power is plotted versus speed in m/s, and in Figure 5-8 it is plotted versus the number of kilometers traveled per sol. For a given distance, the power required for navigation is independent of the rover speed. It is interesting to compare the power required for navigation with that required for motion. For example, a 500 kg rover covering 1 km/sol requires between 4 and 12 watts, depending upon the drive efficiency and rolling resistance. The navigational power for 1 km/sol varies between about 10 and 100 watts, depending upon the number of instructions per meter. That is, the power for drive in the worst case is equal to the power required for navigation in the best case. Consequently, if the rover's speed is to be increased and additional power is available, the power should be put into computation.

- **Combined power requirements**

In Figure 5-9, the combined drive and navigation power have been plotted versus the distance traveled per sol. For the navigation power, it has been assumed that a nominal 150 million instructions are required per meter of travel and 20 watts are required per million instructions per second. For the rover drive power, a 500-kg rover with a drive efficiency of 0.5 and a rolling coefficient of 0.3 (i.e., the worst case) has been assumed. Again, as indicated in the Figure, about two thirds of the power are required for navigation and about one third for the drive. For the particular set of parameters chosen, the power requirement for the rover is about 45 watts/km/sol. This can be reduced by going to a smaller rover, which will reduce the drive power, but the computational requirements for the navigation will remain about the same. Hence, to reduce the power requirements for drive and navigation, the main emphasis should be on increasing the efficiency of the on-board computers.

- **Estimate of required panel size**

In Section 3, it was estimated that 20 W/m^2 is a reasonable value to use for estimating required panel size, a value about midway between the silicon and GaAs cell values. With this value, the array size required for the rover described in Section 5-6 above is shown in Figure 5-10. Again, using 1 km/sol as a basis, the rover drive requires about 0.6 m^2, whereas the navigation

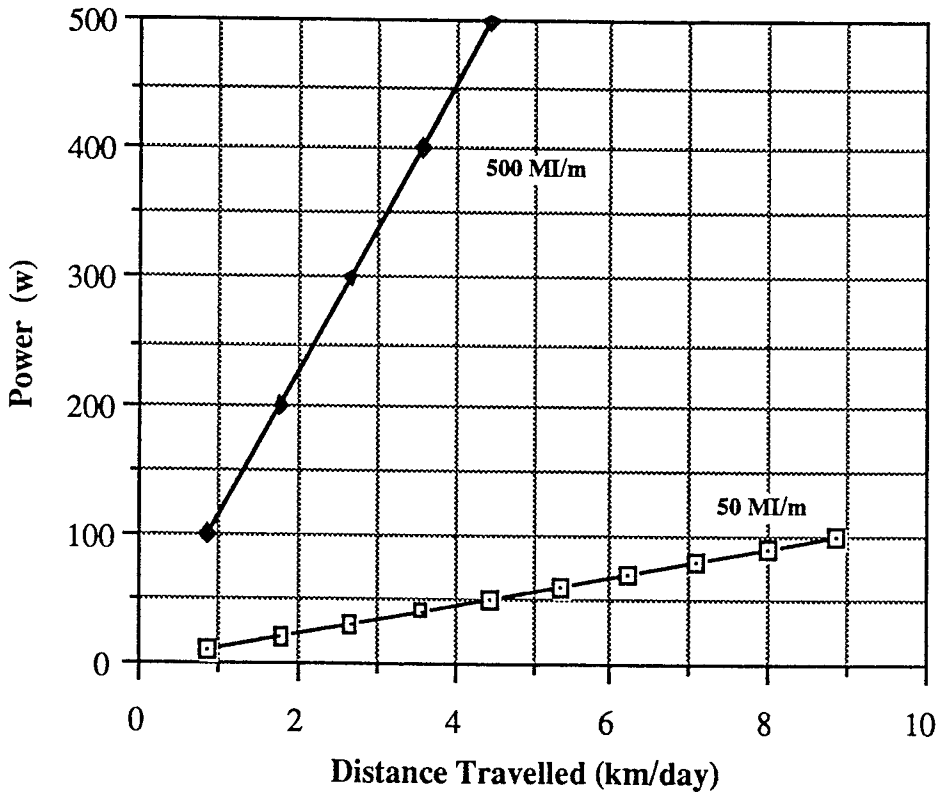

Figure 5-8. The estimated average power requirement for navigation.

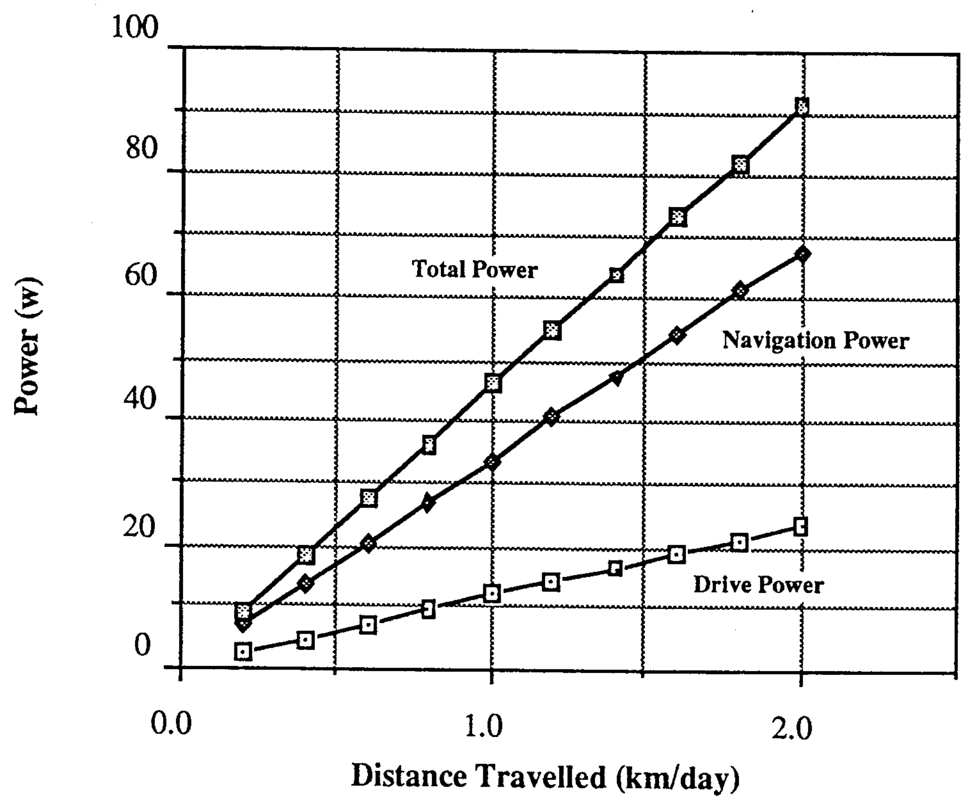

Figure 5-9. The total estimated power for rover drive and navigation. Rover mass is 500 kg, drive efficiency is 0.5 and rolling resistance is 0.30.

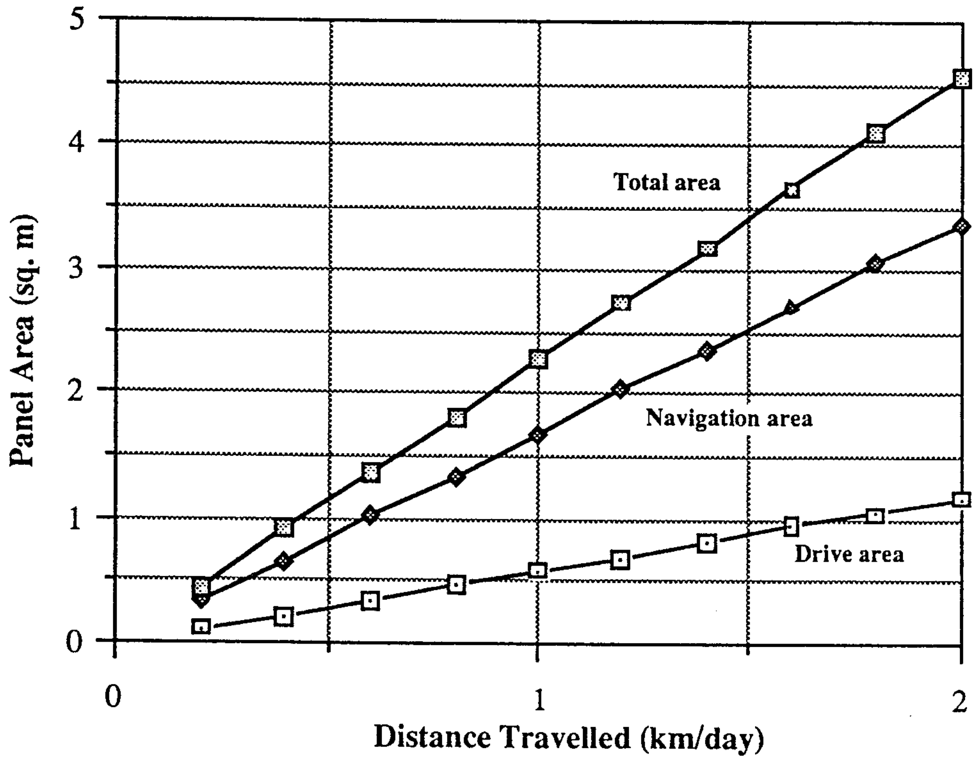

Figure 5-10. Estimated array size required to power the drive and navigation systems. Rover mass is 500 kg, drive efficiency is 0.5 and rolling resistance is 0.30.

requirement is 1.6 m^2. The total area required for drive plus navigation is about 2.2 m^2. Again, the largest reductions in this area can be made by reducing the power required for computation.

5.3 Thermal Control System

The thermal control system keeps the various systems of the rover at an appropriate temperature for operation. The most critical systems for thermal control are the electronics systems, such as the computers and the data storage systems, and the instruments. For these systems, temperatures of about 0° C should be maintained.

Much of the equipment can be expected to keep itself warm. For example, on the MRSR vehicle, the computer is expected to need 75 watts of power. As virtually all of this power will end up as heat, no additional heating is likely to be required. There will be some power requirements for temperature sensors and movement of thermal control louvers for cooling, but this will be small.

Still, 50 watts of thermal control power are specified for the MRSR vehicle. If the thermal control system obtains this from solar electric collectors, then an area of about 2.5 square meters will be needed. This is more than the area needed for mobility. If the heat is obtained from solar thermal collectors, then an area slightly less than a square meter will be needed.

5.4 Power Needs of the Complete Vehicle

The power needs of the mobility system and the thermal control system are only a small portion of the total requirements for the rover. Other systems include the vehicle control system, the data handling system, communications, sample gathering, and the science instruments. Various rover operating modes use these systems to differing degrees and at different power levels. To estimate the average rover power needs, a typical operating scenario as given in Muirhead (1988), the baseline scenario, was examined.

The scenario is for a traverse and the collection of a sample. The total time for this process is 16 hours, and includes time for Earth-based decisions to be made. A plot of power as a function of time is shown in Figure 5-11. The distance covered by the traverse can be found from the time spent in the traverse mode, about 100 minutes, the portion of time spent moving, 50 percent, and the speed while moving, taken as 0.1 meters per second. The traverse is 300 meters, for this case. Note that 72 percent of the time is spent in the idle mode. The power level in idle mode is 250 watts. The average power level for this scenario is 275 watts, only slightly more than the idle power. The average rover speed in this scenario is 0.48 kilometers per sol.

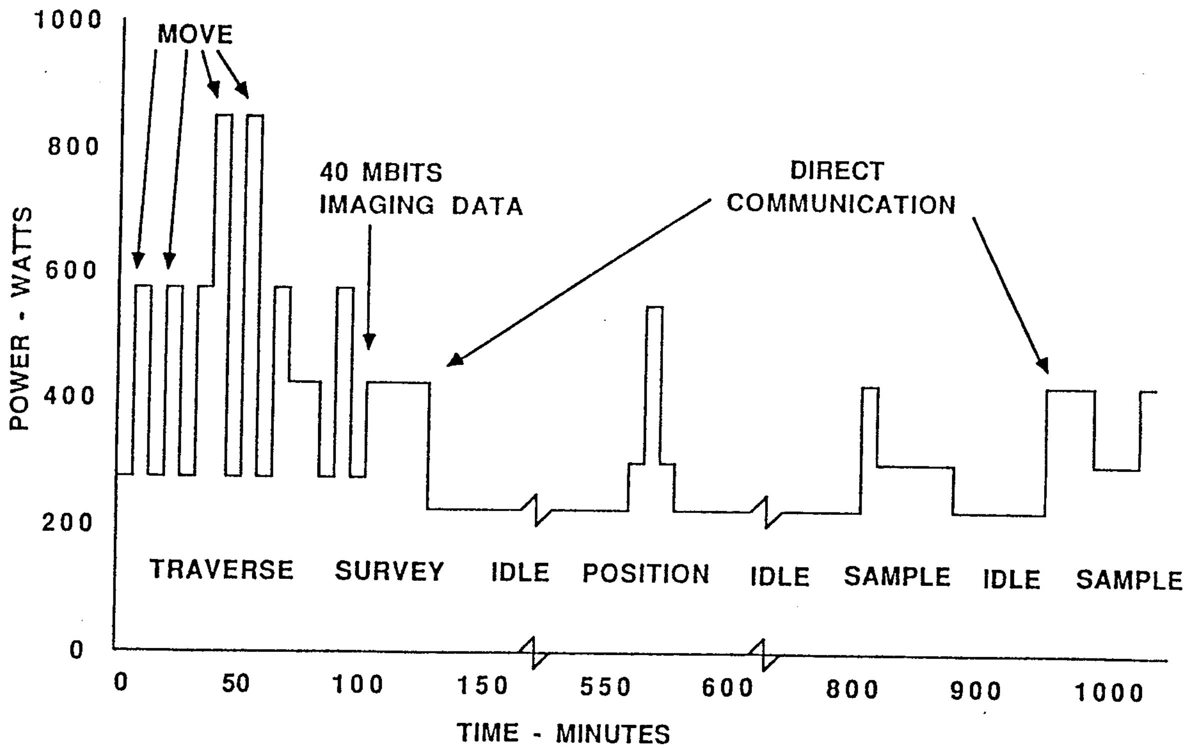

Figure 5-11. Power vs time for the baseline operations scenario.

If the traverse distance is increased to 3000 meters, before the sample is taken, then the average power will increase to 380 watts, and the total time increases to 31 hours. The average speed for this case is 2.4 kilometers per sol.

A number of interesting conclusions can be drawn from these scenarios. First, most of the energy is consumed by systems that are always on, even in idle mode. These systems are computation at 75 watts, data handling at 20 watts, vehicle control at 30 watts, power system losses at 20 watts, science at 10 watts, thermal control at 50 watts, and a 45-watt margin. In terms of reducing power needs, the largest gains can be made by improvements in these systems. For example, the computation power needs could be reduced during the idle mode. The computers are expected to use CMOS technology, which has the characteristic that the power use is almost directly proportional to the clock rate at which the computer is driven. During idle mode, the clock rate could be reduced, saving power. The clock rate could not be reduced to zero, as the computer is still needed to do some tasks in idle mode. If a savings of 60 watts is possible, then the average power needs would be reduced by 20 to 40 watts, for the 3000-meter and the 300-meter traverse cases respectively.

Another conclusion comes from the small difference between the idle power and the average power. One proposed operating mode for a solar rover is to operate only every other sol and charge batteries on the off sol. The benefit from such an operating mode can be quantified by considering what would be the resulting two-sol average power. During the off sol, the power required would be equal to the idle power, 250 watts. During the on sol it would be 275 watts, for an average of 263 watts. This is not much of a savings over the 275-watt requirement of full–time activity.

This situation would change if a new "survival" or "sleep" mode could be specified. In this mode, the rover would close down as many systems as possible in order to save power. It is possible that the power requirements could be reduced to about 80 to 100 watts, with much of this being thermal power. With the sleep mode, operating on every other sol would become a feasible method for saving energy. For example, if the power needs in the sleep mode were 30 watts electrical and 50 watts thermal, then operation every other sol would reduce the electrical power needs from 100 watts average to 65 watts average. Operation only every third sol would reduce the average power needs to 53 watts. The ability to reduce the average power in this manner would be of great use to the rover mission. It would allow the rover to survive long, severe dust storms. In addition, year-round operation at the higher latitudes would become possible.

The low average speed of the baseline scenario is also of interest. The CARD method of navigation is capable of covering 0.2 to 0.4 kilometers per sol if no time is used for sample collection. This distance is similar to the baseline scenario considered above. The range using CARD could be more than doubled if communication with the rover was continuous (by use of a communications satellite), allowing ample time for sample collection. If the baseline scenario is considered to be representative of typical rover operations, then CARD navigation may be sufficient.

The average power is quite high compared to the power needed for mobility. Based on the results given above, the average power needed to move 0.48 kilometers per sol is 25 watts, about 10 percent of the total power needs. The MRSR baseline design includes 500 watts of power production capability. Based on the average power found above, this is excessive. (Note that the power requirements used to get the average did include a margin). The excess power is intended to allow for operating modes that use more than the average power level without the need for a large battery bank. For an RTG-powered system, it is better to have a larger than needed power production capability instead of a large battery bank. However, a large solar array area would result in handling difficulties. In addition, a solar rover will need a large battery bank in any case to provide power at night. For these reasons, the solar array will be sized for the average power requirement, not the peak power.

Based on these results, the power needs for the rover will be assumed to be 275 watts total: 225 watts electrical and 50 watts thermal. This constitutes the baseline case.

Two other cases will also be considered. The second case is a power system that mimics the current RTG power system, capable of supplying 500 watts continuously.

The third case is a low power one. In this case, the idle mode is assumed to be replaced with a "sleep" mode that uses 30 watts electrical and 50 watts thermal, so that the average electrical power need is 100 watts.

5.5 Peak Power and Storage

Neither the production of energy nor its use will be continuous and uniform. As shown in Figure 5-11, the power requirements of the rover vary by as much as a factor of three depending on the task it is doing. There are some cases where the power requirements could be as high as 2000 watts, such as climbing over a large block. The output of the solar panel also varies with time, as its average power output is about 15 percent to 20 percent of its peak output. Thus a panel designed to provide an average output of 320 watts will, at its peak, output up to 2100 watts. Of course, for half the time, the Martian night period, the solar panel produces no power at all. Due to these variations in supply and demand of power, some form of storage will be needed. The storage must be capable of both providing and absorbing the peak power levels given above and must also have sufficient capacity to provide for rover operations through the night. Note that as the idle power is so close to the power needed for normal operations, there is little savings in not operating at night. This situation could change if a "sleep" mode became available.

The storage capacity should be large enough for about 16 hours of rover operations. This will see the rover through the time from late afternoon through the night to early morning, the period when the solar power can be expected to be less than the power demand. Using the above assumption of 225 watts electrical and 50 watts thermal of average power requirements, the capacity of the storage would be 3.6 kWh electric and 0.8 kWh thermal. In order to insure that the storage system will have a long life, that is, a large number of charge-discharge cycles, the depth of discharge should be less than 100 percent. For the electrical storage, a 50 percent depth of discharge is assumed to be satisfactory, bringing the total capacity up to 7.2 kWh. For the thermal storage, a 75 percent depth of discharge is assumed, bringing the total thermal storage up to 1.1 kWh.

The electrical storage is currently defined as being done by lithium titanium disulfide batteries. These batteries can store 100 W-hr/kg at 100 percent depth of discharge (O'Donnell, 1988). Thus 72 kg of batteries will be needed for the rover. The thermal energy will be stored in water using the phase change water from ice as the storage method. This stores 64 W-hr/kg, so the total ice mass required is 17 kg.

If the sleep mode replaces the idle mode, then the required electrical store size is reduced. If rover operations at night are similar to daytime operations; that is, no attempt to save energy overnight is made, then the required electrical store size is reduced to 44 percent of the values given above, 32 kg. If all of the idle time is shifted to nighttime, then the electrical store requirements drop to 13 percent of that given above, 9.4 kg.

If a power system is required that duplicates the capability of the MRSR power system, then the batteries must be able to provide 500 watts continuously. As shown in above, this much power is not needed,but a design that can supply it provides a worst case data point. For this case, the battery mass would have to be 167 kg.

There will be some losses in the storage system. In order to properly define these losses, a full energy flow model would be needed. At the level of analysis of this study, it will simply be assumed that the storage system losses will be about 20 percent of the energy stored. About 60 percent of the energy produced by the solar cells passes through the storage, so the losses are taken as 12 percent of the total energy collected. Thus, to provide 225 watts electrical to the rover on an average basis, 256 watts average must be produced by the panel. For the case with the sleep mode, the panel must provide 116 watts average, so that the rover will receive 100 watts after storage losses.

The peak power requirement for the battery store is about 2000 watts in both charge and discharge modes. This corresponds to 28 watts per kilogram for the 72 kg pack, or a C/3.6 rate (i.e., a rate that would change the amount of energy stored in the battery by 1/3.6 = 28 percent in one hour). Most battery technologies, such as Ni-Cad, lead acid, and nickel hydrogen can handle such rates. Little information is available on lithium batteries, but it is anticipated that no problems will occur.

Section 6
PANEL DESIGNS FOR THE MRSR ROVER

6.1 Area Required

The results of the previous sections give the required power output of the solar panel and the power per unit area for a solar panel on Mars. The required panel size can now be found.

The average power output of the panel will be taken as 22 watts per square meter for GaAs cells and 17 watts per square meter for silicon, in line with the approximation given in Section 3. A more exact value would require better knowledge of the rover is operating position on Mars and the season. These have not yet been determined for the MRSR mission. However, these values are valid for the majority of Mars over the majority of the seasons.

For solar thermal collection, the average energy collected will be taken as 60 watts per square meter. This is the appropriate value for the case of no thermal diode. Again, this value is also valid for the majority of Mars over the majority of the seasons.

In order to provide the needed 256 watts of electrical power, a 11.6 m^2 GaAs solar electric panel will be needed, or a 15.1 m^2 silicon solar panel. For the thermal energy collector, an area of 0.83 m^2 is sufficient. The total solar collector area is thus 12.43 m^2 using GaAs cells and 15.9 using silicon. If the full 500 watts of electrical power are needed, then the panel sizes would be 22.7 and 29 m^2 respectively .

For the case where the sleep mode is available, the area of the electrical portion of the solar panel is 5.3 square meters of GaAs cells, of 6.8 square meters silicon cells. The total area is thus 6.13 and 7.63 m^2, respectively. If a panel design is desired with a width no greater than that of the main body of the rover, then its area would be about 7.6 square meters, comparable to the required panel size.

Figure 6-1 shows a planform view of the MRSR vehicle, with the solar panel overlaid onto it. Three panel sizes are shown with areas of 6.13 m^2, 12.43 m^2, and 22.7 m^2. For both the larger panels, the width is greater than the main body of the rover, but for the smallest one it is narrower than the body.

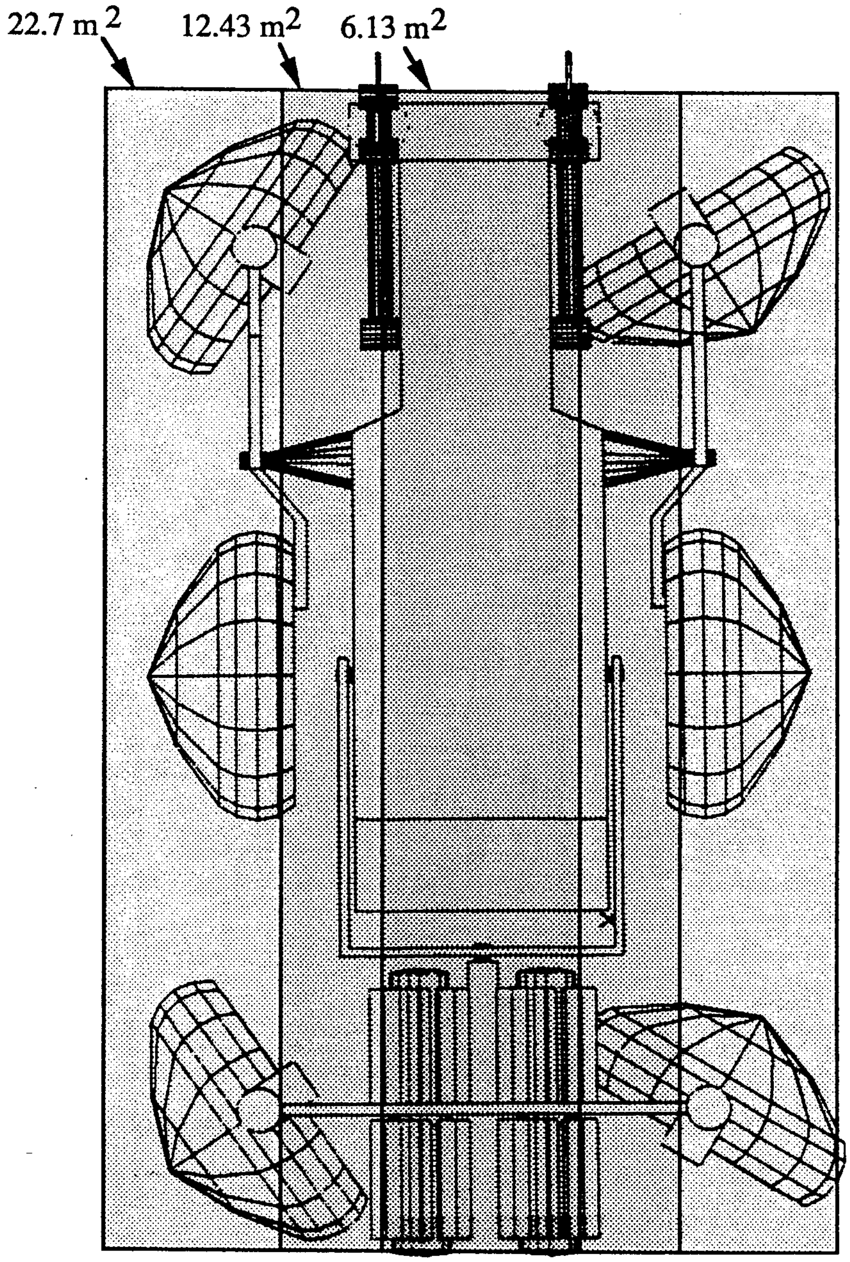

Figure 6-1. MRSR vehicle with solar panels of various sizes

6.2 Power System Mass

The mass of the power system is the sum of the panel mass, the battery mass, and the mass of the electronics. Here only the mass of the first two components will be considered, as they contain most of the system mass and have the greatest variability from case to case. The mass of the panels per unit area depends on the cell type and the level of technology. In the case of GM Sunraycer (Sturtevant, 1989), the electrical portion of the silicon panel had a mass of 1.2 kg per m^2, and for GaAs, 2.3 kg per m^2. The structure mass was 1.6 kg per m^2 in both cases. The cells to be used for the rover will most likely be lighter than those used on Sunraycer. Using data provided by Stella (1989) the mass of a GaAs panel can be expected to be 1.88 kg per m^2, and silicon, 0.98 kg per m^2. Assuming that a similar improvement can be made in the structural mass, a total mass of 2.88 kg per m^2 will be used for the GaAs panel, and 1.98 for the silicon panel.

Table 6-1 shows the mass of the photovoltaic collectors and batteries for several cases covering the two cell types, three average power levels, and a case where the rover is in sleep mode during the night.

Table 6-1

Electrical system mass

Case	Panel area m^2	Panel mass kg	Battery capacity kWh	Battery mass kg	Total mass kg
500 W, GaAs	22.7	65.4	16.7	167	232.4
500 W, silicon	29	57.4	16.7	167	224.4
225 W, GaAs	11.6	33.4	7.2	72	105.4
225 W, silicon	15.1	29.9	7.2	72	90.1
116 W, GaAs	5.3	15.3	3.2	32	47.3
116 W, silicon	6.8	13.5	3.3	32	45.5
116 W, GaAs*	5.3	15.3	0.94	9.4	24.7
116 W, silicon*	6.8	13.5	0.94	9.4	22.9

* Sleep mode at night (no night operations)

The mass of the thermal collector is equal to 17 kg for the thermal storage plus an estimated 4 kg for the collector, bringing the total to 21 kg. Note that the thermal collection and storage system would not be necessary for the 500-watt electric case.

Table 6-1 shows that there is a large range of possible masses for the electrical collection and storage system. Depending on the case, the mass ranges from 241.8 to 22.9 kg, over a factor of 10. The mass of the proposed RTG power system is 129 kg, comparable to the 225-watt case, when the mass of the thermal collection and storage system is included, and some allowance is made for electronics.

The cases where the sleep mode is available show the lowest masses, especially when the sleep mode is used exclusively at night. For these cases, using nickel cadnium batteries is a reasonable consideration. Ni-Cads store only 28 W-hr/kg at 100 percent depth of discharge, and can typically be used at 75 percent depth of discharge. As a result, a Ni-Cad pack will mass 2.5 times the mass of the lithium titanium disulfide batteries.

Section 7
CONCLUSIONS

The solar power available on Mars ranges from a low of zero to a maximum of 700 watts per square meter. Averaged over one sol, the maximum is 225 watts per square meter, during summer in the Southern hemisphere, which occurs near perihelion. Near the equator, the average solar power is 100 watts per square meter or more all year. In any season, over half of Mars receives 100 watts per square meter or more. Most places on Mars get this much for more than half the year.

Atmospheric dust is not a major issue in terms of reduction of surface solar energy. The above figures include the effects of a normal amount of dust. During the planetary storms, the amount of solar energy is reduced to about 60 percent of these clear sky values. Previous estimates of solar energy during dust storms were much lower, as they considered only the direct portion of the solar energy. During dust storms, the direct portion is quite low, but the scattered portion is high, resulting in only a moderate loss.

Silicon and GaAs solar cells of current technology both achieve high efficiency on Mars, with silicon achieving 17 percent, and GaAs achieving 22 percent. The low temperatures on Mars increase the efficiency of the cells, with silicon benefiting to a greater extent than GaAs.

Any energy needed for heating is best obtained from solar thermal collectors instead of electrical heaters, provided the mass to be heated is at a temperature near 0 degrees C. The efficiency of solar thermal collectors is 60 percent to 80 percent, three to four times better than that of solar electric collectors. The collector itself can be quite simple, no tracking, concentration, or even a cover glass is needed, although it is necessary to coat the collector with a selective surface. The thermal store can be integral with the collector, or separate. If integral, the store loses heat throughout the night, resulting in a net collection efficiency of 60 percent. Separate storage allows the efficiency to increase to 80 percent, but requires the use of a pump or some system to transfer heat from the collector to the store as needed.

The rover uses energy for several purposes. Of these, movement uses a small portion of the total, on the order of five percent. The energy used by the computers that carry out the calculations required for movement is two to four times as great as the energy needed for movement itself. Various other systems on the rover (communications, data handling, science, thermal control, and vehicle control), many of which run continuously, consume the remaining energy.

The rover spends most of the time in an idle mode, while signals are traveling between Mars and

Earth, and plans are being made. The power level during idle mode is quite high, 250 watts. In the present MRSR design, little effort has gone into lowering the idle power level, as the power available from the RTG is always 500 watts whether or not it is needed. The average power needed by the rover is actually not much greater than the idle power, 275 watts. This average power use is based on scenario where the rover moves 300 meters and collects a sample, all during a 1000–minute period. In this scenario, 72 percent of the time is spent in idle mode.

The small difference between the average power needs and the idle power needs means that little energy can be saved by operating the rover only every other sol, with the off sol being used to recharge the batteries. This type of operation will only lower the long term average power from 275 watts to 262.5 watts. Reducing the power needs during the idle mode will greatly reduce the average power needs. The introduction of a "sleep" mode, with a power requirement of 80 watts, in place of the idle mode, would reduce the average power needs to 150 watts. Of this, 50 watts would be thermal power, 100 electrical. With a sleep mode, the option of operation only every other sol becomes viable, and would lower the average power to 65 watts electrical and 50 watts thermal.

The solar rover will require a large energy storage system. The main driver on the size of the energy store is the need to survive the night. Even in idle mode, the nighttime energy need is large, so that, based on the average energy needs, 7.2 kWh of battery capacity and 1.1 kWh of thermal storage capacity will be needed. This requires 72 kg of batteries for the electrical store and 17 kg of water for the thermal store. Introduction of a sleep mode would reduce the electrical store size by a factor of two to seven, depending on how much of the idle time is shifted to nighttime.

The losses associated with the storage system can be expected to increase the total energy requirements by 16 percent for electrical energy and a negligible amount for thermal energy. Thus, the total average electrical power requirements are 256 watts for the baseline case and 116 watts for the case with the sleep mode. In both cases, the thermal power needs are 50 watts.

The panel areas for the baseline case are 11.6 square meters electrical and 0.83 square meters thermal for a total of 12.43 square meters. For the case with the sleep mode, the areas are 5.3 square meters electrical, 0.83 square meters thermal, for a total of 6.13 square meters. For comparison, the area of the top of the present MRSR rover, including the top of the RTG's (which would be replaced by the battery packs), is 7.3 square meters. If a panel that could supply an average 500 watts to the rover is required, the same power level as the RTGs, then an area of 22.7 square meters is required. All of these areas are for GaAs cells. Use of silicon cells, the area of the electrical collector will increase by 29 percent.

The mass of the power system, including both the electrical and thermal portions, ranges from a maximum of 253.4 kg for a system that provides 500 watts on a continuous basis, to 43.9 kg for a system that has power for normal rover operations during the day and is in sleep mode during the night. A system that provides for the baseline power has a mass of 126 to 111 kg for GaAs and silicon cells, respectively. For comparison, the mass of the proposed RTG system is 129 kg.

The overall conclusion is that a Mars solar rover is possible, but not easy. If the solar power system is required to duplicate the power output of the RTG system, then it will be large and heavy. If it is sized to supply the energy needed for typical rover operations, then it is of reasonable size and its mass is comparable to the RTG system. If an energy-saving sleep mode is used in place of the present idle mode, then the panel size becomes about equal to the size of the rover body, and the system mass is about half of the RTG system.

Section 8
RECOMMENDATIONS

The model used in this effort for the solar radiation on the surface of Mars had several simplifications. An improved model is needed. A new model should give the distribution of the scattered radiation about the sky, so that the amount incident on a solar panel in any orientation can be found. In addition, the changes to the solar spectrum due to the atmosphere and the dust should be taken into account in finding the photovoltaic cell performance. This is necessary as the efficiency of the cells is a function of the wavelength of light. For panels not oriented horizontally, the radiation scattered off of the ground needs to be considered.

An improved model for the temperature of the Martian atmosphere is needed. Such a model would improve the prediction for the efficiency of both solar thermal collectors and photovoltaic cells. This model should give the mean expected temperature for any time of day, season, and latitude.

The effective use of solar thermal collectors on Mars requires the use of selective surfaces. At present, no such surface is Mars qualified. Investigations of surfaces that can be qualified is needed. The surface must be able to withstand the effects of the Martian atmosphere, the dust, and the radiation.

The thermal control system of the rover could be greatly simplified or even eliminated by covering the rover with a selective surface. This would in effect make the entire rover a solar collector. Such an arrangement should be studied to determine if it is feasible and what problems need to be solved in its implementation.

Although this study has shown a solar-powered rover to be possible, the required panel size is quite large. The panel size can be reduced if the energy needs of the rover can be lowered. In the current rover most of the energy is used while it is in idle mode. A new "sleep" mode has been proposed that would reduce the average power needs of the rover by a factor of two or more, assuming it replaced the idle mode. The feasibility and development of this mode should be investigated.

The current configuration of the MRSR vehicle is not optimum for the collection of solar energy. Rovers that allow for better solar collector integration need to be investigated. Factors that need to be considered are the upper surface area of the rover body, placement of the cameras with respect to the solar panel, and placement of the antenna with respect to the solar panel.

Questions remain concerning the use of solar energy on Mars. The models for the solar radiation distribution need better verification. Also, the effect of dust on the panel performance is not known. The long term degradation of cell performance due to radiation of other effects needs to be better understood for the case of operation on the Martian surface. These questions may best be addressed experimentally. A small probe placed on the surface of Mars could be used for this purpose. The probe would be little more than a solar panel and a transmitter. Every sol or so it would transmit data that gives the amount of energy collected by the panel as a function of time. This probe may weigh only a few kilograms (perhaps even less than one kilogram) and could be sufficiently rugged that it can be lowered to the Martian surface by parachute.

A somewhat more complex probe would be a small rover. Such a rover would be much smaller and simpler than the MRSR vehicle. It would carry no other instruments than a camera and the solar panel. The CARD method would be used for movement. This rover would not only allow for the examination of the usefulness of solar power on Mars, but would give some preliminary information about the surface conditions, as far as mobility is concerned.

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13. ABSTRACT *(Maximum 200 words)*

The possibility of a solar powered rover to be used for the unmanned exploration of Mars is examined and analyzed. The amount of solar power available on Mars is found as a function of time, location and atmospheric dust, allowing the determination of the amount of power that can be collected by either photovoltaic or thermal collectors. It is found that the maximum available power in a normal Martian day varies from 220 to 140 W/m^2 depending on the amount of dust in the atmosphere, while the average annual power is 100 W/m^2. The energy requirements of the rover are determined and used to find the size of solar collector needed to power the vehicle. For the existing baseline vehicle, for which radioisotope thermoelectric generators are planned, it is expected that a 500 W power supply will be required. The actual average power need of the baseline rover is 275 W, and this is taken as the power supply requirements of a solar rover. About 66 percent of the energy consumed by the rover occurs when the rover is in an idle mode. For a solar powered vehicle which can be placed in a low power use dormant mode as needed (during dust storms, night, or in idle mode) 116 W will be adequate. Power saving for a solar rover will be accomplished mainly by increasing the efficiency of the mechanical systems, and by significantly reducing the power demands of the computer systems from 75 to 25 W by closing down parts of the computer system when they are not needed. For the baseline rover, energy storage is achieved by 72 kg of lithium titanium disulfide batteries with a capacity of about 7.2 kWh. It is found that a solar powered Mars rover is possible, with a collector area of 16 to 23 m^2. The actual projected planform area of the existing vehicle is about 20 m^2. At any given time of year, the rover could operate successfully on over half of Mars. Near the equator, this solar rover could operate year-round. The introduction of a power saving “sleep” mode is found to be an effective method of reducing the collector area to about 7 m^2, as well as providing for improved rover survivability in the case of prolonged dust storms or failure of part of the solar panel or battery bank. Future work should include improved models for energy production and use, and design of rovers optimized for solar power.

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